End user Oriented BIM enabled Multi-functional Virtual Environment Supporting Building Emergency Planning and Evacuation

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Summary

Relevant research has identified that high level of building emergency casualty (e.g. due to fire) has direct link with the delayed evacuation especially in residential and high-rising buildings. The traditional fire drill can only passively identify some bottleneck for evacuation after the building has been constructed and under its operation stage; and end-users normally lack of means to be effectively involved in the decision making process in the first place (e.g. building emergency planning and design) and lack of cost-effective and convenient means to be well trained about emergency evacuation at later operation stage. Modern building emergency management research has highlighted the need for the effective utilization of dynamically updated building emergency information. Building Information Modelling (BIM) has become the information backbone which can enable integration and collaboration throughout the entire building life cycle. BIM can play a significant role in building emergency management due to its comprehensive and standardized data format and integrated life cycle process.

This PhD research aims at developing an end user oriented BIM enabled virtual environment to address several key issues for building emergency evacuation and planning. The focus lies on how to utilize BIM as a comprehensive building information provider to work with virtual reality technology to build an adaptable immersive serious game for complex buildings to provide general end users emergency evacuation training/guides. The contribution lies on the seamless integration between BIM and a serious game based Virtual Reality (VR) environment, which enables effective engagement of end-uses. By doing so potential bottlenecks for existing and new buildings for emergency evacuation can be identified and rectified in a timely and cost-effective manner. The system has been tested for its robustness and functionality against the research hypothesis and research questions, and the results show promising potential to support more effective fire emergency evacuation and planning solutions.

Declaration and Statements

DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed……………………………. (candidate) Data………………………….

STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of ………………….. (insert MCh, MD, MPhil, PhD etc. as appropriate)

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This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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Chapter 1 Introduction

1.1. Background and motivation

Building Information Modelling (BIM) follows a revolutionary methodology promoting integration and collaboration for Architecture, Engineering and Construction (AEC) industry (Eastman et al. 2008; RUIZ 2009). It has a huge potential within the areas of building design and building maintenance regarding energy and emergency management (Hailemariam et al. 2010; Rüppel and Schatz 2011a; Wang et al. 2013). Building design decisions are usually made by the designers due to their expertise and according to the specific requirements of the building in question, rather than end-users which are not appropriately qualified but also due to the lack of their effective involvement. Recent BIM developments in software have contributed significantly to building design professionals. Although professionals and clients/end-users can work together to a certain degree to design a building collaboratively, the information provided to clients/end-users is simplified/prepared and static, clients/end-uses lack the effectives means to be involved in the design decision making process in early design stages, and also the means to be aware about the emergency evacuation in the later operation stage. In the context of this dissertation, the term "general end-users" is defined as the people who will use the building on a daily base such as the occupants or maintenance personnel. These are the actual users of the buildings; therefore it is necessary to consider their requirements of living and working within the building.

***General end-user involvement for building design*:** Traditionally, most building designs utilize 2D/3D drawings, which manually pass the documented building information between each party (Eastman et al. 2008) (e.g. Architects, structural engineers, MEP engineers, etc.). However, this kind of information delivery can often lead to conflicts or mistakes. For example, the latest structural analysis from the structural engineer might make the most recent drawings from the architect obsolete if the updated analysis results were not passed back to the architect. This method of using 2D/3D (without semantic information) drawings does not allow general end-users (e.g. occupants) to be fully involved in the design stage due to the technical nature of drawings (Eastman et al. 2008).

With the new developments on design technology, the traditional method of design is gradually being superseded by some innovative methods of design, e.g. BIM which promotes integration and collaboration allowing different applications and disciplines at different stages of the building life cycle to be “linked” through shared information, with a significant amount of current BIM developments being directed to design collaboration and the subsequent economic benefits for design professionals, dedicated BIM based solutions for building design and management for general end-users are relatively less focused upon (Eastman et al. 2008). For example, a functional level BIM is yet to allow a wide range of general end users to contribute during the design and subsequent phases (Christiansson et al. 2011). All data presented to the end users is pre-pared, static and transferred into another format (e.g. specific paper and computer documents) with no real interactive elements for end users.

***General end-user involvement for building emergency management*:** Building design in UK needs to comply with the various regulation requirements of which the fire strategy occupies an important place. For example, the Building Regulations Sections B1 to B5 cover the means of escape, the internal and external fire spread and access and facilities for the fire service. British Standards also cover regulations on escape routes, also applicable to complex buildings. However, the regulations vary from country to country. Moreover, it is hard for general end-users to understand and use them effectively during a fire emergency.

Building emergency management is generally illustrated as an integrated scientific methodology providing reasonable solutions for human safety in extreme environments (Gao et al. 2011). 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 within a building (Kwan and Lee 2005; Gao et al.

2011). Recent research has identified that a high proportion of emergency casualties has a direct link with the delayed evacuation from the facility (Fahy and Proulx 2001; Gershon et al. 2011), which could be caused by the lack of real time two way information updates – building users (including visitors) in an emergency situation cannot get real time evacuation routes, while the external control centres lack real time situation updates, e.g. the real time location of building users. The best example illustrating this is the emergency casualties occurred in the high-raised building with complex building layouts such as the 2001 terrorist attack on the World Trade Centre (WTC).

Generally speaking, fire emergency management utilizes fire drills or experiments to enhance fire emergency planning. However, there has been little discussion about evacuee's 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 (Lawson 2011). In addition, traditional measures only provide solutions after the completion of building design, hence it is difficult to detect conflicts (to the fire emergency evacuation plan in practice) early in the design stage, leading to a modification process which can be very time consuming. Traditional fire drills can help increase the safety awareness, but it does not pro-actively prevent the design fault in terms of fire emergency evacuation from happening. Many BIM development efforts have been directed to architectural, structural, building services and sustainability design, while emergency management related key factors during design stage have not been addressed in depth. Issues such as potentially dangerous evacuation bottlenecks can be overlooked during design stages (e.g. due to the multi and often conflict design objectives), leading to loss of money and time if rectified later on; or cause high rate fire emergency casualty if not spotted at all.

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 emergency situation (Li et al. 2004; Ren et al. 2008) and conduct effective information interaction between the building and the building user (Rüppel and Stuebbe 2008; Rüppel and Schatz 2011a). Kobes et al. (2010c) 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. If combined with BIM, it can provide unlimited options to control the inputs and outputs to achieve results more representative to real fire emergencies (Lertlakkhanakul et al. 2008; Conway 2011; Lin et al. 2012).

General end-user involvement for emergency monitoring**:** Video cameras and motion sensors become the most common devices to visualize and monitor building on large scale now (Olsson and Regan 2001; Dibley et al. 2012). However, video cameras violate privacy when improving security whilst motion sensors cannot provide the same degree of space awareness as video cameras when protecting privacy. Moreover, a huge amount of data generated by building management system, heat and smoke sensors and fire alarms play a pivotal role in getting insight into building energy utilization and emergency detection (Yoon et al. 2009; Zeng and Tabirca 2009). Nevertheless, most existing visualization means to interpret this data is limited to 2D graphs and numerical outputs, which are too abstract to be fully understood by general end-users such as building owners and occupants. Therefore, reliable and feasible building emergency visualization is urgently required to refine building emergency plans; to optimize emergency evacuation; to enable a real-time effective fire evacuation guide during the critical initial stage of a fire disaster for general building end-users. Modern BIM software provides several options to control its output and application interface to enable BIM integration with other technologies in different fields for various purposes, which fosters a large amount of feasible extensions to the current BIM developments (Lertlakkhanakul et al. 2008; Conway 2011; Lin et al. 2012).

This research integrates computer Game Engine technology with Building Information Modelling (BIM) to develop a multi-functional virtual environment. Computer Game Engine is used due to its intuitive controls, immersive 3D technology and network capabilities that allow for multiple simultaneous users. BIM has been specified due to its growing adoption in industry and the 3D-nD models, which suit a game engine's capabilities. The contribution lies on the seamless integration between BIM and a serious game based Virtual Reality (VR) environment which enables better engagement of end-uses. By doing so potential bottlenecks for both existing and new buildings for emergency evacuation can be identified and rectified in a timely and cost-effective way.

1.2. Thesis Statement

1.2.1. Hypotheses

Corresponding to the identified research gaps, which are (1) the end users are lack of effective means to be involved in the design decision making process in early design and evacuation training later in the operation stage; (2) existing BIM adoption lacks coverage for general end-users; (3) for existing building emergency management, there is a lack of timely two-way information communication which plays a critical role in emergency evacuation. The overall research problem addressed in this research is: ***how to enable the easy and effective end-users' involvement in BIM enabled building life cycle process, which in turn can help the building emergency planning and evacuation***? This PhD research therefore proposes the following hypotheses:

- By developing a multi-functional BIM enabled virtual environment (BIM-VE) which leverages the cutting edge virtual reality, computer game and BIM technologies, it will make the involvement of end-users in the design decision making process technically easier as it can virtually immerse users into the system to explore different alternatives with the intuitive computer game liked interfaces.
- With the link to the existing professional BIM design software (e.g. Autodesk Revit), i.e. a BIM enabled virtual environment, the end-users can be well merged into the current BIM based building life cycle design and operation; and the final design can hence better fulfil the end-users' requirements.
- With the underlying seamless and robust two-way information

communication (between building models and end-users within and outside buildings), with the help of BIM-VE connected mobile devices, the evacuation process for building users / even visitors will become much more efficient.

The experiment conducted in this research has been devised into several research objectives listed in the next Section. The methodology adopted follows review, then development and final testing and analysis, which aligns with the proposed hypotheses.

1.2.2. Aim and objectives

The aim of the research is to conclude, define, develop, implement and test a comprehensive software system that can help to address the concluded research problem, to provide a cost-effective and easy way to get end-users better involved in the BIM enabled life cycle building decision making loop to enable a much more efficient building emergency planning and evacuation training, which can ultimately help to mitigate low building emergency casualty.

The main objectives are as follows:

- To conduct a comprehensive literature review to reveal the current research gap and to identify the state of the art technologies, and to devise an appropriate research methodology to facilitate the research development.
- To build up and develop a comprehensive multi-functional virtual environment base on necessary virtual reality equipment.
- To develop a seamlessly integrated BIM and computer game environment to enable the two-way information flow between professional BIM models and end-users involvement (via computer game environment)
- To conduct human behaviour modelling to conclude and test those key factors for a smarter computer game environment.
- To test the entire system and analyse the test results

The overall research target will be achieved by building BIM-based dynamic scenarios via a two way information channel and a well-defined interactive

BIM-based Virtual Environment (BIM-VE) for better building interior design, emergency awareness training and evacuation guidance, and emergency plan improvement. The BIM-VE allows users to have an instinctive way to dynamically see and interact with the building design within a 3D immersive environment gaining a better understanding of the building through its life cycle to improve emergency evacuation strategies within the building design.

1.2.3. Scientific contributions

Overall, the scientific contribution of this research lies on the seamless integration between BIM and a serious game based Virtual Reality (VR) environment, which enables easy and effective engagement of end-users into the life cycle building decision making process. The developed BIM-VE system allows much more effective and multi-functional building emergency planning and evacuation. More specifically,

- The system implemented a robust two-way information channel between professional BIM software (Autodesk Revit) and computer game system (Unity 3D) supported virtual reality (VR) environment which successfully leverages state-of-the-art VR equipment. The changes in the BIM design environment (Revit) can be transferred into user engagement virtual environment in real time; and vice versa.
- The research concluded the key factors for fire evacuation modelling from comprehensive literature review, and further refined those factors with complementary questionnaire; those concepts have been implemented and embedded into the BIM-VE system to provide a smart game environment alongside with the further ontology development based on those concluded key factors / concepts.
- The system provides unique BIM compatible capacity to a computer game system, which allows the implementation of a multi-functional platform to provide different application scenarios, e.g. enhanced building interior emergency design and emergency awareness training; real time and accurate

building information for BIM based indoor navigation and emergency evacuation system; real time visualization for building monitoring; and so on.

- Several key knowledge regarding human behaviour under emergency situation have been concluded out of the initial comprehensive system testing; the result can be used to develop smarter testing game characters to conduct large scale (a thousand representative characters with certain pre-defined human intelligence can be easily deployed into the system) fire evacuation compliance checking during the entire building life cycle, e.g. design, construction and operation stages to identity and timely rectify any potential bottleneck and limitation.

1.3. Thesis Outline

The eight remaining Chapters of this thesis are arranged as follows:

***Chapter 2 Literature Review*: ** The related work is first introduced to outline the new generation of virtual technology based on interdisciplinary science and knowledge to tackle the main problems in practice. Finally, this Chapter builds the basic concept of BIM-based emergency management and defines the technical scope of this thesis.

***Chapter 3 Methodology*:** The overall methodology to create BIM-based virtual reality environment for building emergency management is introduced in this Chapter. Following this methodology, the detailed work flows are specified to make different components of the proposed framework work together to enable various emergency management solutions for both existing and new buildings throughout building life cycle. This Chapter also shows the design of supporting computing hardware and the overall server/client based software infrastructure.

***Chapter 4 System Design and Development*:** This Chapter demonstrates two main parts of system development, which are: (1) multi-functional BIM based virtual environment (BIM-VE) for building emergency evacuation design, training and guidance and (2) scenario-based fire evacuation experiments for building the ontology of fire evacuation behaviour.

Chapter 5 System Testing and Validation**:** several case studies for system usability testing are conducted to refine better ways to organize the system components to provide effective virtual reality environment to support life cycle building design, operation and emergency management. The case study based validation for fire emergency evacuation and planning, includes dynamic scenario generation using semantic and geometric building information via two way information channel for design collaboration between professionals and end-users, for emergency behaviour modelling, for dynamic 3D emergency route planning on multiple platforms, and for practice usage of BIM-VE connected to mobile device for efficient fire evacuation.

Chapter 6 Experiment Result Analysis**:** The analysis of current experiment results employed qualitative and quantitative methods. As for quantitative methods, deductive case study based experiment results are described to validate, correct, or extend the previous research results about emergency human behaviour. In terms of qualitative method, except for recording, pre-questionnaire and post-questionnaire were utilized to investigate unobservable emergency factors in detail.

The conclusion and future work are detailed in **Chapter 7** and **Chapter 8** respectively.

Chapter 2 Literature Review

This Chapter reviews related work in the area of BIM, emergency management, game engine, ontology and their possible integrations. Section 2.1 introduces the features, barriers and futures of building information modelling (BIM), and shows a BIM software survey to find development direction and methods. Section 2.2 then studies the traditional and modern emergency management, and lists the critical factors influencing fire evacuation. Section 2.3 demonstrates the common application of game engine and serious game (i.e. architecture visualization and human behaviour research). Section 2.4 explains generic review for ontology; and Section 2.5 explores the current integration of BIM and virtual environment for various purposes.

2.1. Building Information Modelling (BIM)

As the mainstream direction of contemporary building design, BIM has been brought into AEC (Architecture, Engineering and Construction) industry and regarded as an innovative approach. It has changed the way of designing buildings to some extent and brings about the second design revolution ever since CAD had been brought into the industry (Eastman et al. 2008). Precisely, it provides a "platform and process of collaboration", which can subdivide a project or a single design into smaller pieces that include the specific digital information and assign them to a participant that is specialist in a certain filed. With collaboration mechanism (i.e. Work-set, Linking and Teamwork), the experts can work on the different parts of a single project without interruption of other participants, and then simply assemble their works together into a core model. This parametric core model is "intelligent", and real time changes in one specific part of a design distributed between experts will automatically be reflected the central BIM model. Therefore, different designers expert in different technology fields using different BIM software do not have to worry about the process of a design too much because most of the integrations and coordination will be automatically done by the system (Eastman et al. 2008). However, the development of BIM still faces some issues that need to be solved urgently.

2.1.1. Collaboration, interoperability and integration

There are three main types of collaboration between entities that exist in design workflow of BIM. They are the collaboration between team members, between disciplines, between organizations (Homayouni et al. 2010).

The communication and collaboration between team members were not initially a problem because the participants within a design team usually use the same software for the same type of tasks (such as Revit or Bentley BIM software) and they can always exchange their ideas and designs much easier than any others; in fact, the adoption of BIM has not completely alter the way of collaboration between team members, but make it more convenient and elevate it to a higher level (Eastman et al. 2008).

The situation would be totally different if the collaboration is between different disciplines. Taking architects and structural engineers for example, traditionally, the structural engineers require a preliminary design from architects as a starting point for their analytical models; inevitably, models will change due to the iterative nature of the design process. In practice, whenever the architects come out with a new drawing revision, they would e-mail the model to other teams, and hence all the participants will have to find a way to read or import the architects' drawing and modify their designs in order to comply with this new revision; If this is the case, errors, mismatches and many other unexpected problems are likely to occur, leading to ineffective methods of working (Singh et al. 2011).

In terms of collaboration at an inter-organization level, different companies have different BIM workflows employing different BIM software according to different standards. There is no doubt these differences make the collaboration between different international companies difficult and inefficient. However, if the BIM standards and relative workflows can become standardised, it will largely improve the collaboration of organizations (Barlish and Sullivan 2012).

As for interoperability and integration of BIM, IFC (Industry Foundation Classes, originally developed by International Alliance for Interoperability, IAI; Latest Release IFC4 in the end of 2014) format as an open specification, has been widely accepted by the AEC industry and become an international standard (Khemlani, 2004). Although BIM can export their data to a standard format (i.e. IFC) and allow other applications to read or import, the problem of data loss between different BIM applications developed by different companies has not been solved (Plume and Mitchell 2007). However, in the field of collaboration of BIM applications developed by the same company, there has shown the significant success to some extent. Taking Autodesk Revit as an example, the Revit platform (Revit Architecture, Revit Structure and Revit MEP) uses its own .rvt data format for the cross – disciplinary data exchange and collaboration; and the .rvt can provide seamless collaboration for the Revit platform through Revit Work-sharing (i.e. workset and linking) to integrate the workflows of above three disciplines. Other BIM applications such as ArchiCAD developed by Nemetschek Graphisoft has a very similar mechanism called "Teamwork" that functions similarly to Revit (Graphisoft). In this circumstance, the IFC format acts only as a bridge when the Revit needs to exchange data with other applications.

2.1.2. Barriers of BIM development

To understand the barrier of BIM is the first step to find possible development direction of BIM application. We can then make the effort to tackle these problems. Finally, they can, more often than not, contribute to the development of BIM. The barriers can be mainly classified into 3 different categories: Legal Issues, Commercial Issues and Technical Issues (Ashcraft 2011).

Legal Issues: Collaborative works play a pivotal role in BIM, so ownership issues, confidentiality issues and responsibility issues are more likely to become the breakthrough points in the field of law (Ashcraft 2011). As for ownership issues and confidentiality issues, a BIM model usually contains all sort of information that owned by different individuals or parties. As a result, it is very difficult to address patents that may belong to different participants or experts and cannot be shared by other specialists. Moreover, it is even more difficult to address which individual or party will be responsible for the design while the information owned by them get involved in the core BIM model (Gu and London 2010). Ideally, the BIM system should only grant the participants limited rights to access the core BIM database; in other words, they should only be able to access/extract certain information they legally need; and should not be able to view the rest. But current technologies are not sufficient to achieve this ideal sharing method; yet, this is all about data mining and this is the technology that being developing at the moment (Cerovsek 2011). Apparently, lacking a standard contract template and a legal framework, the elimination of these barriers might not yet be possible. This, in turn, develops into one of breakthrough points which researchers should contribute to. For the responsibility issues, Howard and his colleagues (Ashcraft 2011) suggested that it should be allocated rationally based on the benefits received from BIM. Similarly, it also requires an industrial standard and legal framework to bring it into line.

Commercial Issues: The commercial issues focus on economic benefit aspects because of the business final goal of profit-pursuing (Ashcraft 2011). BIM has proved that it is time-saving and cost-effective. Indeed, BIM can maximize the efficiency as well as curtailing manpower and rent cost and many other aspects in certain situations; all of above together will definitely contribute to the profit-pursuing goal. However, an explanation will be needed for why the commercial obstacle is one of the major obstacles lie before BIM adoption (Gu and London 2010). The first issue is about profit. It have been pointed out that the issue is caused by the immediate benefits conflict among owner, contractor and design professional body (Eastman et al. 2008). The client's benefits to BIM can bring them fewer errors and argues, also the BIM model can be used for future purposes such as construction process and facility management. Similarly, with the aid of BIM, the project requires less coordination and engineering effort, and hence the contractor will be able to channel more efforts into shortening construction period. So the immediate benefits for owners and contractors are obvious. Nevertheless, for the design professional bodies, the benefits are not as immediate. On the contrary, the adoption of BIM means a significant investment on hardware and software, the employees must be trained before they can actually use BIM applications; the design company therefore has to restructure the workflow and redesign the working process around BIM. All of these heavy tasks need a great amount of time, energy and investment to be accomplished before the company recovers its investment and brings a profit. Consequently, the design company will take a huge risk if it is decided to deploy BIM whereas the other two parties (owner and contractor) can greatly benefit from it without sharing their economic profits (Azhar 2011).

Many consultancies started realising BIM is the trend of the industry and shown great interests in it. They understand BIM still has unbeatable advantages in many aspects in the design phase. They treat BIM as an “investment for tomorrow” (Mihindu and Arayici 2008). Trying to find an acceptable method to solve the profit issue and paving the economic distribution way to BIM become another breakthrough points for the development of BIM (Eastman et al. 2008).

Technical Issues: BIM applications are not optimized for every parts of design (Ashcraft 2011; Eastman et al. 2008). In other words, there will always be few tasks that cannot be done by any one of BIM applications in a project and participants have to use certain software package which may not be a BIM application for certain task. This, in turn, generates more problems with regards to coordination. Given this situation, how to fully develop BIM applications in every task grows to be the breakthrough point of BIM research. From a more pragmatic standpoint, empirical evidence abounds that BIM applications especially in architectural and structural area can provide seamless collaboration because BIM software (e.g. the Revit family through Revit work-sharing) can integrate the work flows of different disciplines (Ashcraft 2008; Singh et al. 2011). However, there is still a blank to extend this collaboration to various civil engineering areas such as energy conservation and emergency efficiency. So why not regard these as the direction of our research in BIM?

Another relevant technical issue is archiving of data. The digital archiving technologies totally depend on external energies and equipment while those external factors are being considered unstable in some circumstances (e.g. outage and failure of electronic equipment) and people cannot access to the information without these factors. 2D drawings and documents generated by computers can be printed off and hence transfer onto our traditional media (i.e. papers), which can partly solve the problem. However, archiving works of BIM in traditional media partially are impossible because they include too many dimensions out of data many of which are not in printable format. This proves to be another breakthrough point.

2.1.3. BIM software review

BIM software developed by different organizations has their own separate collaboration mechanism, improving many aspects of construction project from the conceptual design to the end of project process. However, due to lack of basic common collaboration standards and rules, they are hard to work in the same BIM workflow, which fundamentally impedes the development of the BIM collaboration (Ashcraft 2011). Therefore, it is necessary to do a comprehensive survey about BIM software to find a feasible and flexible BIM workflow between BIM software regardless of developer. For this, the following steps should be followed (Figure 2.1). First, according to literature review, some common and special parameters for BIM products' evaluation should be set. Second, collecting BIM product information as much as possible from electronic papers, websites and personal usage experiences become a long-term task. Third, these data should be organized and compared in a single file such as excel and topic map to find best workflow for BIM applications. Finally, it is possible to take advantage of these comprehensive data to develop a BIM collaboration workflow across different BIM companies.

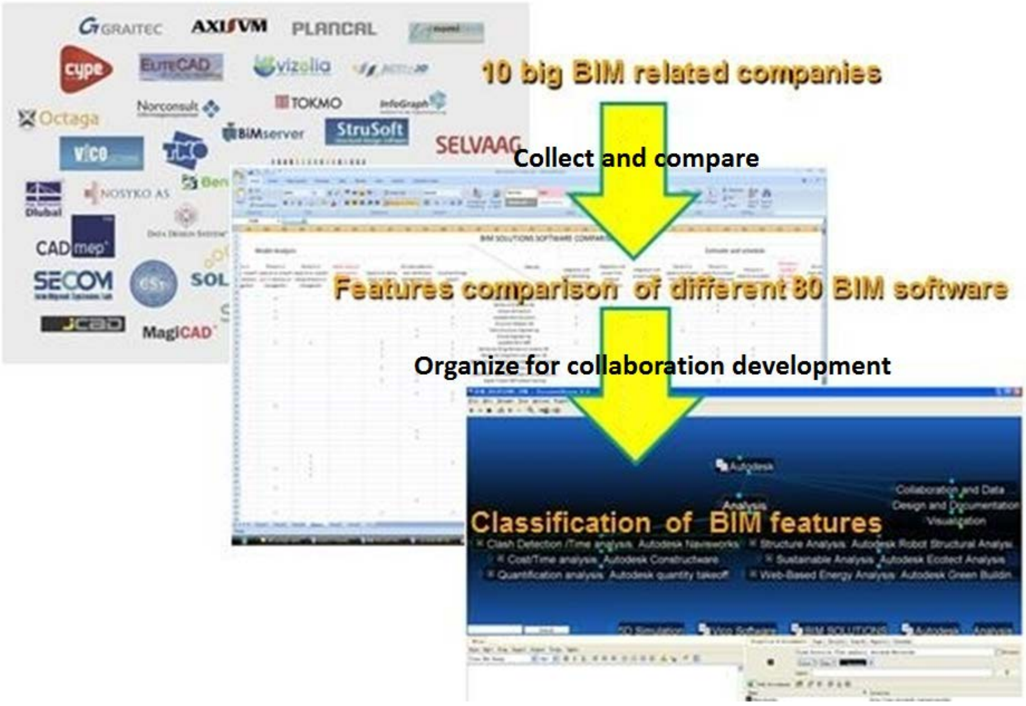


Figure 2.1 The steps to undertake BIM software review

The important parameters which can conclude functional features of BIM products have be organized and compared in a single excel file to find research interests (Appendix A). Specifically, the vital evaluation parameters throughout building life cycle can be classified into four categories:

Parameters in Model Creation: bidirectional associativity; workset setting; designing and documentation capability; designing (modifying) parametric model in 2D & 3D capability; detailed libraries; powerful tools; photorealistic design visualization; animations for creating visual presentations; intelligent elements; collisions check; report and analysis; ability to record and reuse histories; workgroup collaboration; multiple filtering options; addressing large projects capability; interoperability services; multiple criteria adjustment and support; conceptual design modelling support; rendering capability; transparency capability; accelerating & accurate model creation technology support; capacity to generate multiple schedules(lists); and capacity to generate all necessary views (sheets) of construction.

Parameters in Model Analysis: extract model information from local or other company models; integration with structural analysis applications; integration with energy analysis applications; integration with Microsoft software; the built in capacity to present structural analysis or management; the built in capacity to present quality analysis or management; the built in capacity to present energy analysis or management; model analysis optimization; capacity to define space utilization; 3D clash detection and interference management; and cloud technology support.

Parameters in Estimate and Schedule: integration with cost estimating applications; integration with project time schedule applications; integration with project quantity applications; the built in capacity to present time schedule as 4D automation; the built in capacity to present cost estimates and management; the built in capacity to present quantity take off; estimate or schedule optimization; 4D simulation, clash detection and interference management; 5D analysis and management during stimulation process; and reports generation and export.

Parameters in Project Management: sensitivity analysis or management; visual basic for application; capacity to allocate accountability; advanced security; publish, share, and view models and drawings from different application; advanced information search and filtering; transferring data integrity; temporary construction analysis (such as crane ,elevators position); mark up and annotate comments; resource management capability; XML Import/Export; Supports green building mark-up language (gbXML); IFC compatibility; multiple data formats support; the ability to integrate with design and management software of other companies; present precast elements coordination; document (information) archive and management; updating and tracking models; database repository; geographic information systems (GIS) such as Google Earth and ESRI support; renovation & refurbishment workflow support; and Internet browser viewer support (Web formats support).

Currently, this excel file includes a comparison of BIM solutions between 10 BIM companies and 80 BIM software, details which is shown in Appendix A. The classification of BIM software were generally classified into several groups, which include Design and Documentation, Energy Analysis, Cost and Time Analysis, Cost and Quantity Analysis, Quantification Analysis, 4D and 5D simulation, Multiple Analysis Simulator, Collaboration and Data Management, Visualization, Facility Management, formation Extractor and their extensions for existing Software. In order to make the comparison of BIM software more understandable, Figure 2.2 was created according to software information of the excel file by a software named Personal Brain. It is a kind of topic map which illustrates BIM solutions developed by different companies, which makes different BIM solutions more intuitional and searchable. All references and relations of current BIM solutions were organized in this software, which can build a database interface for the future development of BIM solutions.

It is the researcher's personal opinion that the current top three companies concentrating on BIM are Autodesk, Bentley and Nemetschek. These three companies have different mechanism for collaboration and 3D modelling, and their overwhelming technology advantages in these areas push other software companies have to develop other aspecs of BIM. With the development of IT technology such as multi-dimensional modelling and cloud computing, most other BIM competitors are focusing on other aspects of BIM tool development other than model creation and BIM collaboration. Therefore, the important models specified in different area has emerged, including AIM (architecture information model), SIM (structural information model), FIM (facilities information model), BSIM (building service information model), and BrIM (bridge information model). All sorts of information included in different models can be integrated into a single data set and hence enable different organizations to extract useful information for their own purposes and perform their own activities (Eastman et al. 2008).

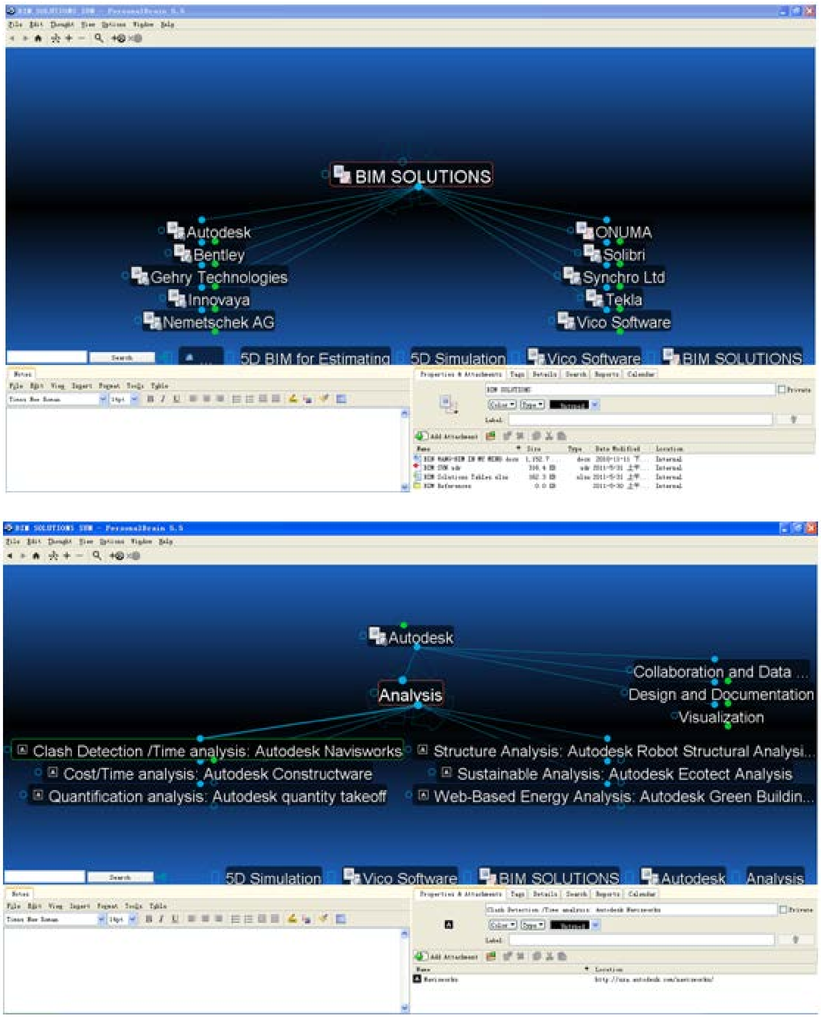


Figure 2.2 BIM solutions in Personal Brain

With cloud technology, BIM software can develop a convenient and fast platform for end users. BIMserver which is an open source building information model server gives end users a chance to carry out the collaborative building design via a web browser. It is free (published with the GNU GPLv3 license), small sized (around 45M) and an easy operating (web-browser interface) software. More importantly, a web browser is the only necessary thing if users want to connect to the web interface of the server. The open standard native IFC is the core of BIMsever because it is easy to use and can descrease delivery information loss between end users. Another distinct feature is that BIMserver creates unique URL for every IFC object. Then, users can get details and information of specific models using these REST (Representational State Transfer) links and they can use O3D (API to create interactive 3D graphics applications in a web browser) to view these models inside the appropriate web-browser without downloading other special software. Thus, the BIM model can be demonstrated online without sending large files among users. In addition, users can use model export formats (i.e. Google Earth network link) to get the updated but complete model information which means the BIM models are placed in the cloud (Bimserver).

BIMserver also has some popular functions of the modern BIM software. It provides a platform which allows multi-user to work on the same core model but different users are responsible for their own part. Beyond their own part, they can view but cannot edit the other users‘ part. If they want to do so anyway, a permission message has to be sent to other users. Provide that it is allowed, users who are not responsible for specific part have the temporary right to edit the permitted part now. Furthermore, all users will receive an updated notification when the core model has been changed. Users can make use of RSS feeds to set warning of core model’s change they are interested in.

BIMserver has several export formats including ifcXML, CityGML, Collada, KML and Google Earth network link, which make model information easy to be delivered among different software in order to satisfy the design requirements. For example, the data is easy to import in Skechup using Cllada format; Google earth can be used as free viewing software if export format of models is KML or Google Earth network link; CityGML is regarded as open data model and XML based format for storage and exchange of virtual 3D city models; ifcXML has be supported by many software like Eurostep Model Server，XML SPY 2005 and ArchiCAD. Besides, BIMserver have the function of collision detection, models mergence and difference find between revisions. With the help of BIMserver on the internet, a computer can do more better and faster things in the field of BIM because BIMserver based on web browser can save hard drive size and CPU speed as well as making transferring BIM information fast and easy in the cloud.

2.1.4. Summary

Currently most design projects still use older more mature methods of design such as

Computer Aided Design (CAD) based drawings, which can lead to errors by drafters (e.g. architect, structural engineer, MEP engineer, etc.). The 2D drawings make the stakeholder cannot fully participate in the design because it is often difficult for them to understand the drawings. BIM aims to make the design more collaborative between different parties by using central models where everything is built in 3D. The digital parameters of central model allows for greater interoperability between the different parties and packages. The use of the same or linked model should help reduce delivery and re-digitized design errors between different parties. Specifically, it permits for a design to be modified and updated for all parties so that they can see the changes almost immediately and see if those changes affect their elements of the design. BIM provides clash detection between various versions of the model created by different parties. For example BIM allows for checking for clashes between the architectural and structural models or the service model with the other two. BIM also allows for the non-technical parties to understand the design by seeing design in 3D and getting a proper visualization of the whole project.

Additionally, BIM can facilitates conducting structure, energy, cost and quantity analysis. It can also assist scheduling of the works and project process control, which is known as 4D or 5D design. This can be used to create animation of project to help clients understand the construction process. However, the development of BIM faces legal, commercial and technical issues, which should be addressed urgently by specialists. Moreover, BIM has not yet allowed for a client to contribute to the design phase. So the clients cannot explore the building from their perspectives. The building design is what a designer thinks that clients want/need to see rather than what clients really want to see.

2.2. Emergency management

Currently, most BIM software are focusing on developing the collaboration and subsequently economic benefits (such as saving the cost of time and resources), inevitably neglecting some other aspects that are closely related to building safety such as building emergency management. The unbalanced economic development, natural resource damage and earth environment changes have produced a series of public sudden affairs and natural disaster; therefore the timely and efficient emergency management is urgently needed to keep the safety of individuals and avoid the loss of properties.

Technically, emergency management employs interdisciplinary technologies and sciences to carry out the timely forecast, warning, and disaster control and processing to reduce and eliminate damage of emergency and disaster (Godschalk 1991; Haddow et al. 20081; Gao et al. 2011). Periodically, emergency management can be divided into four phases according to the development of disasters, which are disaster mitigation, disaster preparedness, disaster response, and disaster recovery (Jr. and Streib 2006, Mejri 2011). On macroscopic scale, emergency management can be seen as a kind of public management means, which maintains social stability, protects the fruits of economic development, and safeguards the people's lives and property safety. On microscopic level, emergency management can be seen as a kind of optimization behavior, which integrates various engineering method to realizing whole emergency goals (Gao et al. 2011). With current changes in the security situation worldwide, emergency management has increased its significance to civilians in public infrastructure. This is especially particularly significant in addressing fire disaster which is common and related to lives and property safety of all occupants.

2.2.1. Emergency drill to investigate human behaviours

The use of emergency drills has been widely used and regarded as the current normal method to explore critical factors influencing human fire response. Pauls (1999) indicated some elements of fire drills can contribute to the study of human behaviour in fire, showing the descriptive information on space and time factor is critical to understand why certain emergency behaviour occurs and how it can be integrated with performance based design. Proulx (2001) illustrated that the fire drills can investigate the occupants' emergency behaviour to improve design and implementation of fire safety systems if fire drills are originated in different parts of the building with the unannounced fire alarms. Actually, Proulx (1995) had pointed that emergency drills plays an important role in understanding potential problems in real fire, educating and training occupants, and obtaining data for evacuation simulation models. Perry and Lindell (2003) identified emergency drills can be utilized to optimize community preparedness and emergency planning, and can educate/train the occupants at the same time.

Generally, the approach for study human emergency behaviour is to video the participants (as evacuees) during a drill, then to ask them to complete a post-questionnaire to supplement the result. The reason to employ post-evacuation questionnaire is to investigate non-observable factors influencing emergency behaviour (Proulx 1995; Shields and Boyce 2000; Olsson and Regan 2001; Gwynne et al. 2003; Xudong et al. 2009). Recently, Xudong et al. (2009) used this approach to investigate human behaviours in an emergency drill with announced evacuation in a retailed store in China. The video analysis included total evacuation time and total number of customers evacuating from each exits while analysis of questionnaire was consisted of common actions of occupants shopping with an accompanier, common actions of occupants shopping without an accompanier, pre-movement time, cues for emergency, and exit way choice (i.e. the most familiar exit, the nearest exist, and the exist directed by staff).

Shields and Boyce (2000) used the video and questionnaires to survey human behaviours in an emergency drill without announced evacuation in a retailed store in the UK. The parameters to record human behaviour results in emergency drills were similar to those settings in the Xudong's findings, which included commitment to activities being undertaken, first cues of emergency, common actives of shopper with accompanier, reasons for the exit choice (i.e. familiarity, proximity, detection by staff), pre-movement times for the four stores, and the evacuation time. Other interesting findings contained that some of the exits were not used for evacuation since there were not any staffs to direct them there; some evacuees showed a reluctance to pass disabled evacuees which was one of reason that caused the delay of evacuation time.

Proulx also utilized the video and questionnaire approach to study fire drill behaviour in four mixed occupancy residential buildings (Proulx 1995). He indicated the video camera was critical to capture human emergency behaviour and reported the ambiguous alarm delayed the evacuation. Besides, it was shown that evacuees had a trend to evacuate as a group using the familiar stairs and exits. Likewise, Olsson P A and Regan M A investigated pre-movement delays and total evacuation times in three university buildings (Olsson and Regan 2001). The pre-recorded evacuation messages were employed as part of the alarm to investigate efficiency of alarm system. Both different tasks and environments of the evacuees can influence the pre-evacuation time. The results of this study were used to validate the study of a simulation modelling tool.

Similarly, Gwynne et al. (2003) employed video and questionnaires to investigate pre-evacuation time and behaviours in a university and in a hospital. They found that the role of people and the occasion had an influence on pre-evacuation. For example, patients did not respond to fire alarm until informed by hospital staffs while most of students in the university began to escape after hearing a fire alarm. They tended to finish current or priority activities such as shutting computers down or collecting expensive items.

Other studies employing video recordings of human behaviours in fire drills focus on more specific data such as merging and deference behaviours in stairwells (Melly et al. 2009; Boyce et al. 2011). The studies used discretely positioned video cameras to capture human behaviours in fire drills. Several behaviours affecting merging such as allowing people with babies to pass and a man pausing to let five women pass were noticed by Boyce et al. (2011). These human behaviours are similar to deference behaviour Melly et al. (2009) reported. For example, a security guard in fire drills waited to allow sixteen (mostly female) evacuees pass. Similarly, a group of female evacuees stopped to let an entire floor of evacuation. Moreover, both studies have proved that floor flow rate increased if the stairwell was located adjacent to the incoming staircase (Melly et al. 2009; Boyce et al. 2011).

Except for the video and questionnaire analysis approach, laboratory and experiment studies have been utilized to investigate human behaviours in fire. Muhdi et al. (2006) investigated difference between maximums and normal speeds of walking and crawling to reveal the influence of occupant characteristics on the evacuation models by recording the time of participants' walking or crawling across 100ft in fire evacuation experiments. Kobes et al. (2010c) conducted experiments to detect the effects of smoke and low-level signage on evacuation. Three conditions for the experiments included no smoke, with smoke, and with smoke but also with exit signs at floor level. The results demonstrated that the majority of people used the main exit in the experimental environment without smoke; used the nearest exits within smoke; used the nearest exit in the experimental environment with smoke and the lowered exit signs.

Emergency drills were not only used to explore human behaviours in fire emergency but also in other kinds of emergency. In terms of emergency behaviours in transport applications, Boer (2005) investigates driver behaviour when facing a simulated truck fire that block their way by emergency drills. They found that motorists often stayed in their car until an announcement describing incident was made. It was observed that the participants saw others' exiting behaviours and copied their behaviours. In an aircraft emergency drill, Muir (1996) conducted a series of experiments to investigate the factors influencing aircraft evacuation behaviour. To create competitive environment, Muir applied a technique in which an incentive payment was made to the certain percentage of participants who can evacuate earlier than others. The effects of bulkhead apertures and seating configurations on evacuation rates, the effects of smoke on evacuation rate, and the effects of assertiveness and presence of cabin staff were investigated employing this technology. Some behaviour in this emergency drills such as climbing over others or the backs of the seats to evacuate were reported in real emergency.

2.2.2. Virtual simulation for emergency management

The most pivotal aspect during building emergency is the success of safe escape. In practice, it is common knowledge that the current measures required by law do not always provide the support for people in burning buildings. For example, the rescue operations by fire-fighters and emergency treatment by paramedic can only be provided after the initial stage of a fire that is an important factor in terms of survival (Purser and Bensilum 2001; Pires 2005). Moreover, in several countries, the legislation provides for a ‘depend-in-place-strategy’ for specific locations such as schools and hospitals (i.e. fire emergency strategy varies depending on different functions of areas of the same building). An evacuation strategy for buildings with assembly occupancy is usually unlisted, which poses a big fire hazards to those places that have not adequate support for human evacuation behaviours (Kobes et al. 2010a).

With the development of science and technologies, recent researches provide a novel building emergency management combining human behaviour research with the simulation technology (Li et al. 2004; Ren et al. 2008). Li et al. (2004) proposed a prototype of behaviour based human motion simulation for fire evacuation procedures. Ren et al. (2008) developed a virtual reality system with spread fire and smoke to simulate emergency evacuation based on interactions between the users and the fire virtual environment. With this trend, several simulation tools based on human behaviour modelling appeared such as buildingEXODUS developed by FSEG (Fire-Safety Engineering Group) in UK, FDS+Evac developed by VTT in Finland and REPKA (interactive pedestrian simulation) and simulator developed at the TU München within the project REPKA-interactive pedestrian simulation for regional evacuation (Rüppel and Schatz 2011a; Rüppel and Schatz 2011b). Nevertheless, the weaknesses and limitations of these simulations or simulation tools are focusing on precisely representing human behaviours in emergency, which exist in traditional emergency drills and experiments as well, since the human behaviours in emergency are not deterministic components which can be described based on various principles (Lawson 2011). Therefore, a more feasible method that can really reveal human behaviours under emergency should be proposed and developed.

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-rise buildings (Purser and Bensilum, 2001). 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, a variety of websites, questionnaires, telephone interviews, and face to face interviews (F.Fahy and Proulx 2005; National Institute of Standards and Technology 2005; Averill et al. 2009). The comprehensive process of data collection mentioned above consumed a huge amount of time and money, and was restricted to this specific scenario. 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 emergency situation (Li et al. 2004; Ren et al. 2008) and conduct effective information interaction between the building and the building user (Rüppel and Stuebbe 2008; Rüppel and Schatz 2011a). However, if it is combined with BIM, it can obtain unlimited options to control the inputs and outputs, which could be an efficient method to achieve results more representative to real emergencies (Lertlakkhanakul et al. 2008; Conway 2011; Lin et al. 2012).

Though video games have emerged for more than thirty years, it was very hard for non-professional programmers to utilize game technology to conduct scientific research until recent years, because the editors used to modify the games (Game Engine) have become sophisticated but conversely simple enough for different end-users (Conway, 2011). BIM proposes several options to control the output of 3D geometry from digital models for multiple purposes while game engines with advanced compatible originally utilized for editing games become sophisticated but conversely simple enough for general end-users to edit game components. Thus, this provides researchers without knowledge of developing games a chance to combine Game and BIM together to complete a series of scientific research in the field of architecture design, human behaviour research, and simulation experiments (Lertlakkhanakul et al. 2008; Shiratuddin 2008; Boeykens 2011; Conway 2011;

O'Keeffe and Shiratuddin 2011; Rüppel and Schatz 2011b; Yan et al. 2011; Tang and Ren 2012). Moreover, the computer-aid management for emergency or disaster events such as fire, explosion, flood and terrorist attack has increased its significance to civilians in public infrastructure (Feng et al. 2008; Schütz et al. 2008; Yuan et al. 2009; Rüppel and Schatz 2011b; Tang and Ren 2012). Following the above trend, BIM as cutting-edge technologies in the building design area can potentially integrate game engine to extend its functions to the field of building emergency management by optional inputs and outputs of digital information from BIM software. Actually, several researchers have utilized 3D building geometries extracted from CAD but not BIM to carry out some preliminary simulations and analysis (Ren et al. 2004; Feng et al. 2008; Ren et al. 2008; Tang and Ren, 2008; Shi et al. 2009;Tang and Ren 2012).

2.2.3. Critical factors influencing fire evacuation

Previous emergency events analysis have revealed that there is a relation between human behaviours under emergency and a high number of fire deaths and injuries, especially in the residential houses, hotels and high-rise buildings (Purser and Bensilum 2001). Presently, the knowledge of human behaviours during building emergency events such as fire is still relative limited and developing. In terms of optimising building emergency management, it is critical to find why certain seemingly disastrous incidents have led to very few casualties. This question referred to identify the critical factors that influence fire response performance because the appropriate fire response can decrease the time of fire evacuation that influences the level of casualties a lot.

Fire response performance is a human ability to realize the sighs of danger and subsequently make a decision to escape from fire (Kobes et al. 2007). Specifically, it can be concluded as following four main activates and periods (Sime 1995; Meacham 1999; Pires 2005; McConnell et al. 2009; Johnson et al. 2011):

- Seek information on the event (information seeking period)
- Consciousness of danger by external cues (cue validation period)

- Response to danger indicators (decision-making period), which includes:
  - Collect belongings
  - Provide verbal instructions to evacuate (managerial role)
- Escape to a safe place (escape period)

In general, fire response performance is related to three aspects:

a) The nature of fire;

b) Human nature;

c) Building characteristics.

According to Kobes et al. (2010a), critical factors that influence fire response performance in terms of fire, human, and building features can be expressed in the Figure 2.3.

Figure 2.3 Critical factors influencing fire response performance

a) The fire features influence fire response performance can be classified into:

- perceptual features
- fire size and growth rate

- smoke yield, toxicity, and heat

- *perceptual features.* The perceptual features include elements that can be seen, smelt，heard or tangible, which influences the time to discover the fire. The uncertainty about the emergent situation is one of main reasons to delay the start of evacuation (Tong and Canter 1985). Considering fire response performance, cues such as feeling the impact of the planes, hearing the explosion, swaying of the building and smelling burning fuel facilitated rapid evacuation (Gershon et al. 2007). Other words, those with a higher perceived risk responded more quickly than those with a lower perceived risk (Gershon et al. 2011). However, Stress (and the contributory time pressure) was argued to result in a narrowing of the perceptive field, which would mean that fewer cues are utilised in an emergency (Ozel 2001).

- *fire size and growth rate.* The first scientific research for human behaviour in the case of fire reveals that the size of a fire is related to the behaviour of the personnel in the building, and focuses much less on the relation between building design and a safe escape (Bryan 2002). The fire growth rate is the main factor to determine the fatality of emergency events since a lot of fatal incidences was caused by rapid fire development. The fire rate can be decided by a formula based on exponential growth that influenced by fire growth coefficient of burning material (Tang and Beattie 1997; Chang and Huang 2005).

- *smoke yield, toxicity, and heat.* The reduction of sight as smoke yield and respiratory irritation caused by toxicity often has negative impact on occupant's evacuation performance. The fear generated by breathing problem and reduced vision often enforces the occupants to change their escaping direction or re-entering the dangerous area in fire (Erik Magnusson et al. 1996; Gwynne et al. 2001; Isobe and Helbing 2004; Rubini and Zhang 2007). The research reveals that people tend to walk alongside walls for guides when they cannot get enough sight during fire disaster and their movement speed is lower than in normal condition. In addition, the sound signal near fire exits will speed up the speed of evacuation (Isobe and Helbing 2004).

b) Apart from fire features, human features play a pivotal role influencing fire response performance since they are directly related to how occupants behave in the case of fire. Generally, Human features can be subdivided into

- Individual
- Social
- Situational features
- *Individual.* Overall, the individual characterises during evacuation in fire involve their knowledge and experience, their observation and judgement, and their mobility.

In terms of individual characters, Gershon et al. (2007) stated that previous experience of emergencies was a factor which contributed to a rapid response. However, Wood P G indicated that previous experience of a fire incident hindered immediate evacuation since fighting the fire or minimising the risk is often associated with previous experience of a fire incident (Wood 1980). Moreover, the arising physic stress during fire event disturbs how an occupant responds to around situation (Proulx 1993). Ozel (2001) argued that some stress can increase vigilance, although too much can lead to a "hyper-vigilant" state, in which people do not make use of the available information, due to rapid processing, or filtering, of information. Moreover, most people play a follower role and do not respond to dangerous signals until others taking actions (Cornwell 2003; Johnson 2005).

As for social characters, Pan X et al. also predicted that higher crowd density and high emotional arousal can result in behaviours which do not contribute to the safety of an evacuee or other building occupants (Pan et al. 2005). Moreover, occupants may not follow instructions telling them to stay in place, particularly if they have observed other people evacuating (Tubbs and Meacham 2009). It has also been found that what significantly influences the choice of evacuation way is not the distance to exits but how it is perceived. It has been observed that evacuators often choose the relatively straight corridor and familiar route to get out of the building in emergency events (Sandberg 1997; Løvs 1998; Graham and Roberts 2000).

The first research into the evacuation of functionally impaired individuals began in the 1970s. Indeed, people with physical disabilities or impairment and old age may have difficulty descending a large number of stairs, and this significantly increased the evacuation time (Tubbs and Meacham 2009; Gershon et al. 2011). Moreover, Averill J et al. (2009) reported that barriers to mobility may come from pre-existing injuries, medication/medical treatments and occasionally wheelchairs, pregnancy or older age.

- *Social features*. The main aspect of social features includes collaboration/group preferring, social bond, and commitment to prior activities.

Social structures, interactions and pre-existing social relationships below a crowd level exert a strong influence over behaviours, and altruistic and group-oriented behaviours will predominate rather than highly individualistic, selfish behaviours (Sime 1995; Shaw 2001; Pan 2006). Group bonds are so strong that a separated member may re-enter a building to reform the group such that members can exit together. Besides, assistance from co-workers and emergency responders supported evacuation (Averill et al. 2009). ENT (Emergent Norm Theory) explains that in unusual circumstances collective behaviours occur as people re-define their situation and interact to form a new social structure which guides their behaviour (Aguirre et al. 1998).

Normally, if there are strong social bonds (such as relatives) between different people, evacuators will try to respond to fire as a group (Sime 1983; Sime 1995; Sandberg 1997). And this affiliated behaviour influences the choice of evacuation route as well (Cornwell 2003). Wood conducted a large-scale research in Great Britain into human behaviour in the case of fire in 1972 while Bryan carried out a comparable study in US, which identically indicated that occupants with relatives tend to re-enter the building to search missing family members. Their escape behaviours include the tendency to walk through smoke and try to extinguish fires if they are in around residential fires (Tong and Canter 1985; Bryan 2002). Drury et al. (2006) conducted qualitative analysis of the interview data to demonstrate that co-operation during fire was attributed to the continued influence of pre-existing social roles, in addition to solidarity addressing shared threat. They concluded that pre-existing relationships were shown to delay fire performance response due to the time required to process information and the greater efforts help friends and colleagues, rather than evacuate immediately. However, Aguirre et al. (1998) found the opposite that pre-existing social relationships between people in groups who knew each other well enabled groups to utilise resources more efficiently.

Purser and Bensilum (2001) reported that people in buildings have a commitment to their prior activities and need to recognise the importance of an event to stop these activities. Other words, occupants have a tendency to finish their job they are doing before stating evacuation (Graham and Roberts 2000). However, these who continued working reported a significantly lower perception of risk than those who did not and then put themselves in a danger (McConnell et al. 2009).

• *Situational features.* The critical situational features involved awareness of fire, physical and role position, presence of leaders, and familiarity with layout of building

Several researchers found that awareness of fire is a more critical evacuation factor than the time cost of moving to safe places (Fahy and Proulx 2001; Purser and Bensilum 2001). Hearing screams of "fire" was a greater motivator to action, causing people to be aware of the fire. Moreover, some research found that a bell or a 'slow whooping' signal is recognized as a sign of danger while communication system broadcasting tend to be a more efficient way to ask the occupants to take seriously evacuation behaviours although it is not currently allowed in case of fire (Proulx 2000; Proulx 2001; Proulx and Laroche 2001; Averill et al. 2007). Proulx et al. (2001) cited studies which support the prediction that voice communications will improve evacuation behaviour, although pre-recorded messages were not recommended as they will not be specific enough to guide people to safety.

As for physical position, it has been found that those people who are standing or walking are more like to leave the building in emergency events than the people whose position is sitting (Sandberg 1997). In terms of roles, Proulx (2007) revealed that the behavioural response of an occupant to a fire depends upon their role in the building: visitors are more likely to wait or expect instructions, whereas employees (based on their sense of responsibility) are more likely to act quickly.

Presence of leadership in evacuation promoted occupants to walk down stairs

(Gershon et al. 2007). In fact, lack of leadership was found to be one of the main factors which caused delay to evacuation (Gershon et al. 2011).

In terms of familiarity with layout of building, occupants normally choose the familiar routes and the main exists that is the usual entrance to get out of the burning building (Sandberg 1997; Graham and Roberts 2000). One of reasons for this is that some evacuees' worries about their ability to walk out of the building with unfamiliarity (Gershon et al. 2007; Gershon et al. 2011). Ozel (2001) also argued that decisions tend towards the less risky option when under evacuation time pressure, which may contribute to the common selection of familiar exit routes in an emergency. Pan et al. utilized the theory of bounded rationality to explain that individuals exit through the same way they entered the building rather than evaluate all alternatives (Pan 2006).

c) In terms of building features, the elements determine the fire response performance includes:

- the situational features
- the engineering features
- *the situational features.* Specifically, the situational features contain occupation density, easy of way finding, the presence of a Building Evacuation Team, and the level of fire safety engineering on fire safety.

The researchers have revealed that there is a direct relation between high occupation density and high probability of fatality in the case of fire (Sandberg 1997; ARUP 2004). Pan (2006) indicated that higher crowd density can cause non-adaptive behaviours. Moreover, Galea et al. (2009; 2011) explained that the crowd density can cause natural breaks, which inevitably enabled evacuees to rest and decrease the speed of evacuation. In congested conditions, the ability to choose was limited due to the crowd density, resulting in some commuters using the escalator during evacuation (Kinsey et al. 2009). Kuligowski (2003) further explore that evacuation speed is based on the density of their particular location.

Difficulty locating fire exits and poor signage were primary causes of delays to initiate evacuation (Gershon et al. 2011). Literatures have shown that evacuees cannot notice the emergency route sight on the ceiling and employ them to carry out evacuation behaviours (Ouellette 1993; Johnson 2005). Moreover, it is evident that the presence of a well-trained emergency response team exerts positive influence on the rapid evacuation (Sime 1991; Sandberg 1997; Fahy and Proulx 2001) and rational usage of emergency exits (Sandberg 1997; Graham and Roberts 2000). In addition, the fire safety facilities have to been arranged and maintained in a good order in order to fulfil requirements of rapid fire evacuation (Patel et al. 2000).

- *the engineering features.* The engineering features of a building involve: layout, installations, materials, and fire compartments and size (Kobes et al. 2010a)

Specifically, the components of the layout can be divided the escape route signage, the design of escape routes, the design and location of the emergency exits, and the emergency staircases. Pan (2006) demonstrated that higher environmental constraints (such as dim lighting, too narrow exits, poor signage) can result in behaviours which do not contribute to the safety of an evacuee or other building occupants.

The installation includes escalators and lifts, fire and evacuation alarms, emergency lighting, and sprinkler system etc. Considering installations of engineering features, physical safety features such as lighting, handrails on the stairs, reflective tape, and floor lighting increased evacuation progress (Gershon et al. 2007; Averill et al. 2009). Fire alarms may not actually warn of a fire since most occupants have been reported to not ware of fire without additional cues (Purser and Bensilum 2001; Proulx, 2007). Proulx (2007) used several studies and reports to provide reasons why occupants fail to respond, which include: a relatively low percentage of people recognise the signal as an alarm; occupants do not know the correct response to an alarm; a lack of confidence due to false-alarms; and inability to hear the alarm. He further found that the behavioural response of an occupant to a fire alarm is dependent upon their role in the building: visitors are more likely to wait or expect instructions, whereas employees (based on their sense of responsibility) are more likely to act quickly (Proulx 2007). Purser and Bensilum (2001) reported that people who were slow to respond to alarms because they failed to recognize importance of an event to stop their activities and misunderstood the developing speed of fires emergency. Moreover, the safe use of elevators and the study of defend-in-place strategy were conducted. The discussion of making the elevators available for evacuation during the fire emergency dates from 1980s (Proulx 2001). The fact that more than 3000 people were saved by self-evacuation and use if elevators in south tower during WTC9/11 disaster is most important empirical evidence to prove that proper usage of elevators can enhance possibility of survival (Averill et al. 2007). Proulx and Reid (2006) revealed that lift use was associated with floor level, with more people on higher floors using them.

The materials herein constituting the engineering features are those used for construction, finishing and furnishing of a building but may cause fire disaster (Kobes et al. 2010a). Besides, there are very little number of researches focusing on fire safety and fire safety engineering (Sime 2001).

2.2.4. Summary

Building emergency management concerns several main aspects, such as emergency pre-planning, timely information communication and emergency human behavior. Emergency pre-planning is an action plan devised as a precautionary measure before any disaster and is activated in response to a major incident only. The normal approach to address emergency preplanning includes traditional emergency drills and virtual simulation. The emergency drills are to record the behaviours of participants (as evacuees), which usually includes the completion of a post-evacuation questionnaire to supplement and supply the results that are hard to be observed, such as perception of emergency cues during the drills. 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 aspect 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.

In terms of virtual simulation, recent computing developments have enabled virtual environment to be utilized for preplanning simulation. However, the building information for such a system is static and limited, which means it cannot dynamically change emergency plans according to the changed building design. The virtual simulations for emergency evacuation during the fire are developing. However, the timely information of communication becomes the main problem because the emergency model cannot be updated in real time, thus it cannot provide the up-to-the-minutes evacuation guidance in the real word. In addition, the simulations can only work on 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.

The emergency behaviour modelling has been used for virtual simulation. Questions have been raised about how to precisely represent emergency behaviour to simulate a fire evacuation (Lawson 2011). It should begin with review of the critical factors that influence emergency human behaviour. Traditionally, these critical factors were investigated by emergency drills, which is time and cost consuming. Recent computing developments have enabled computer gaming systems to be utilized to explore human behaviour during a fire emergency, which might be possible way to improve the accuracy of human behaviour research.

2.3. Use of Computer Game Engine

Although video games have been available for almost thirty years, it was hard for non-professional programmer to create games for purposes. Fortunately, this has been changed recently since the editors used to modify the games have become sophisticated enough but conversely simple enough to be considered useful for different end-users (Conway 2011). Currently, these dedicated game editors, named Game Engine, have made possible to creation of games for non-professional, which allow them to easy insert architectural design elements into the video game, and then enables significant architectural visualization in game environment (O'Keeffe and Shiratuddin 2008; Boeykens 2011; Conway 2011; Rüppel and Schatz 2011b; Shiratuddin 2011; Yan et al. 2011). Better still, these releases were not specifically for the benefit of architectural designers, but rather were to support people wanting to use the Game Engines to fulfill their research gaps such as spatial interaction management and building emergency management (Lertlakkhanakul et al. 2008; Rüppel and Schatz 2011a; Tang and Ren 2012).

2.3.1. Architecture visualization

Several successful research studies that integrate with CAD/BIM and game have shown that Game Engine can serve as an enabler to improve architectural visualization and emergency management to a higher level. Specifically, on the one hand, BIM provides several options to control the output of the 3D geometry, which is a valid approach to provide multi-purpose output from its core model. On the other hand, Game Engines support importing meshes and 3D geometry in certain format from external software including BIM software to game environment. Therefore, it is feasible to propose a workflow to combine BIM and game when Game Engine supports whatever formats the BIM software outputs. With unique technologies such as physic engine and artificial intelligence, it is possible to extend functionality of current BIM software employing a Game Engine. With the advanced compatibility of technology, it is realistic to propose using game technology in professional design offices (Schreiber 2009). The following sub-sections introduce several developing methodologies utilizing different Game Engines to build a bridge between BIM and game to enhance architectural visualization.

Unity 3D: As one of the most famous Game Engine, Unity3D is characterized by its cross-platform system, available in free and non-free versions. Moreover, games can be exported as standalone applications for OSX and MS Windows, for consoles such as XBox and Wii, and for smartphones running iOS or Android. More importantly, it supports web applets for online use, which can decrease the size of a game and promote its spread. In this Game Engine, "Assets" are referenced to external files, such as scripts, textures and models. They are assembled into different game scenes or levels for different purposes with the integration of internal game objects. The imported assets is actually referenced instead of being fully embedded and they can be reloaded after some assets changes (Unity3D 2011). Figure 2.4 illustrates how this Game Engine works with some CAD/BIM software. The FBX format seems ideal to translate geometry and material information from BIM/CAD model into the Game Engine. However, in practice, when importing FBX format into Game Engine, it cannot automatically attach materials to the corresponding surface of objects.

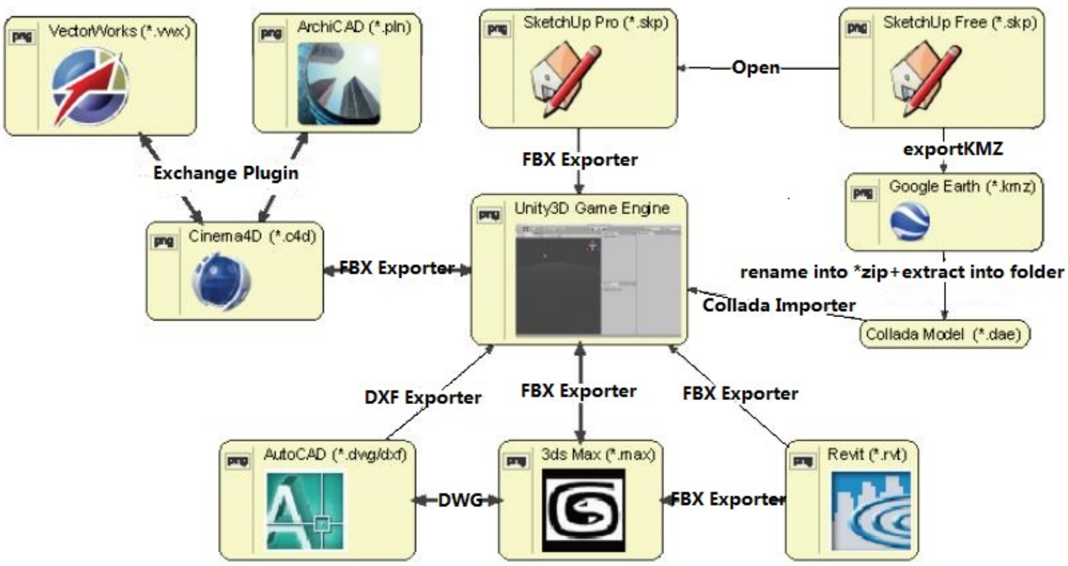


Figure 2.4 Unity3D Game Engine and preferred integration with CAD/BIM software (Boeykens 2011)

In the future, when this Game Engine is combined with linking and filter of CAD/BIM assets (i.e. elements), a very flexible system can be created. It is possible to link one filtering version of the BIM model with lower resolution and less detail to the real-time game environment to save CPU usage of a computer, while at the same time hosting a higher-resolution version for photorealistic rendering in BIM environment (Boeykens 2011).

XNA: The XNA Game Engine developed by Microsoft allows developers to develop games for both PC and Xbox360 video game consoles. Better still, the XNA and its related tools are free for everyone. Therefore, XNA Game Engine is regarded as a cost-saving but efficient tool to combine BIM to game. There are two ways to integrate XNA workflow with CAD/BIM model to enhance architecture visualization: (1) XNA workflow based on FBX format; (2) XNA workflow based on Revit API.

1) XNA workflow based on FBX format

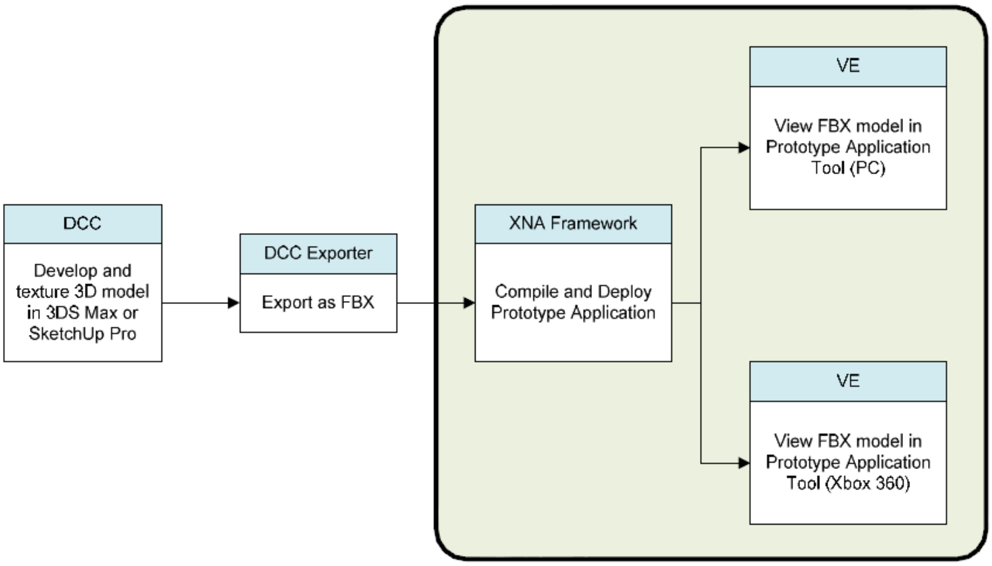


Figure 2.5 CAD model conversions art path (O'Keeffe and Shiratuddin 2008)

This way is similar to the Unity3D process to integrate a CAD/BIM model into a newly or existing virtual game environment. Figure 2.5 shows a XNA workflow using both SketchUp and 3DS Max as the Digital Content Creation (DCC), and FBX format as the bridge to connect BIM to game. Firstly, 3D models created in SketchUp Pro and 3DS Max can be exported into the FBX file format by DCC exporter (i.e. FBX exporter). This FBX exporter allows users to preserve geometry scale, texture mapping, animation and lights. The exported FBX model can then be easily loaded and viewed using the prototype application tool based on XNA framework via both the PC and the Xbox 360 (O'Keeffe and Shiratuddin 2008). Thus, multiple 3D models can be arranged and modelled in 3DS Max or SketchUp, and then sent out to XNA game environment as one FBX scene to improve architecture visualization for different purposes.

2) XNA workflow based on Revit API

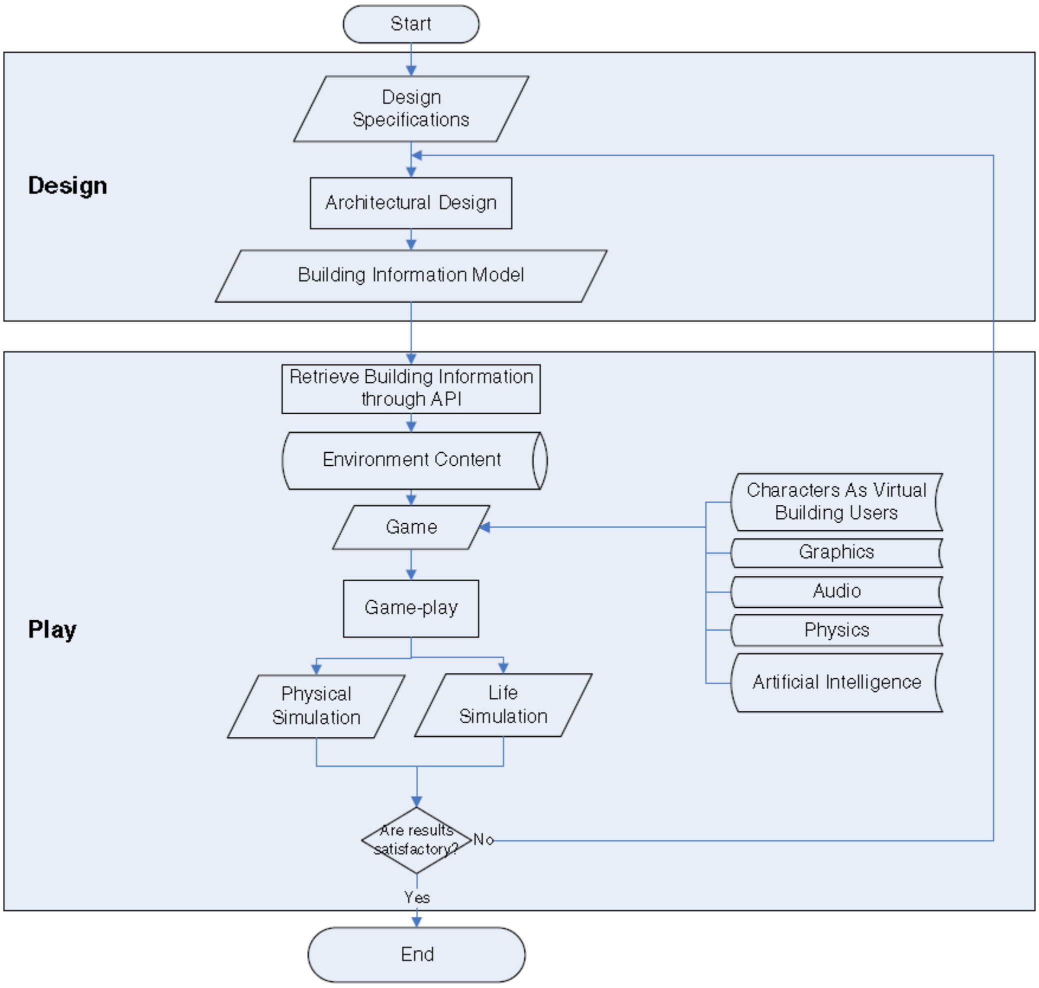


Figure 2.6 Architectural design-play(game) process (Yan et al. 2011)

There is another BIM-Game prototype based on Revit API and employing XNA Game Engine to supports a new architecture design process illustrated in Figure 2.6: Design-Play (Yan et al. 2011). The process starts with the design phase and end with play phase. Firstly, designers develop an architectural design according to design specifications in design phase. BIM allows designers to build 3D models with non-geometric information such as materials of building elements according to their requirements, which can be regarded as a filtering BIM model. In the Play phase, designers use different specific filtering models to generate required game environment, and then play games with the BIM models for different purposes such as collision detection and facility management for the disabled. The XNA Game

Engine can introduce virtual characters (building users), and other game components such as graphics (lights, shaders and camera views), audio, physics, artificial intelligence in this BIM-Game environment. It can simulate physical dynamics of a building and behaviours of virtual building users as well. The Design-Play process would not end until the results are satisfactory with requirements of designers.

A solution for interoperability between Game Engines and building models is the Revit API. It plays as a crossover (Figure 2.7) that processes intermediate information and facilitates communication between the BIM and game environments. BIM module connects to this crossover to send and receives updated building information while Game module connects it to interact with the BIM model in real time. Thus, with application of this crossover, end-users can utilize this unique Design-Play process to evaluate the model's design in real time (Yan et al. 2011).

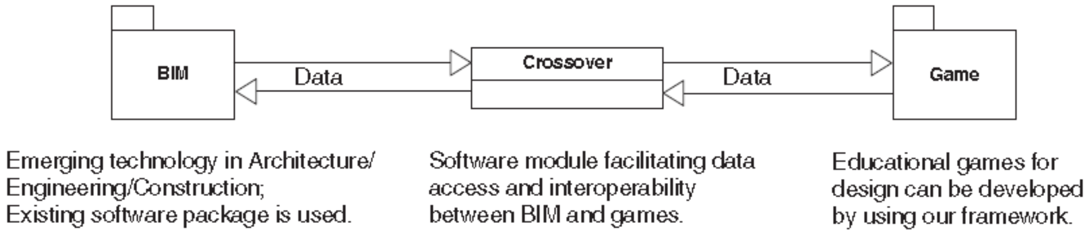


Figure 2.7 The BIM-Game modules and interoperability (Yan et al. 2011)

Ogre3D: This BIM-based game application is modular in general and consists of several components: a graphics-engine is responsible for the graphical display on the screen and provides interfaces for loading, managing, displaying and animating textured 3D models. The BIM-based game environment shown in Figure 2.8 uses Ogre3D as its graphics-engine (Rüppel and Schatz, 2011b).

The presented BIM-Game prototype implements two interfaces for BIM data transferring. The first interface uses Autodesk Revit API to process the BIM data. One advantage of using the Revit API is that the extracted building information from BIM model does not only include the geometry (symbol) of the building elements but also their semantic (structure and intelligence). Another big advantage lies in possibility of making use of Autodesk FBX (i.e. a platform-independent 3D data interchange technology) to facilitate data exchange between several Autodesk content creation tools like Autodesk 3ds Max or Maya. With the development platforms and interfaces fulfilled by Autodesk Revit API, it was found out that only one single BIM-application is needed to gather all required information to build the game scenario.

The second interface, which is under development, provides support for Industry Foundation Classes (IFC). BIM can export their data to a standard format (i.e. IFC) and allow different BIM applications developed by different companies to read or import so as to enhance interoperation of BIM applications that might employ different BIM workflow. Following this way requires more work in mapping the building elements with their rendering properties stored in an additional database for material and texture definitions (Rüppel and Schatz 2011b).

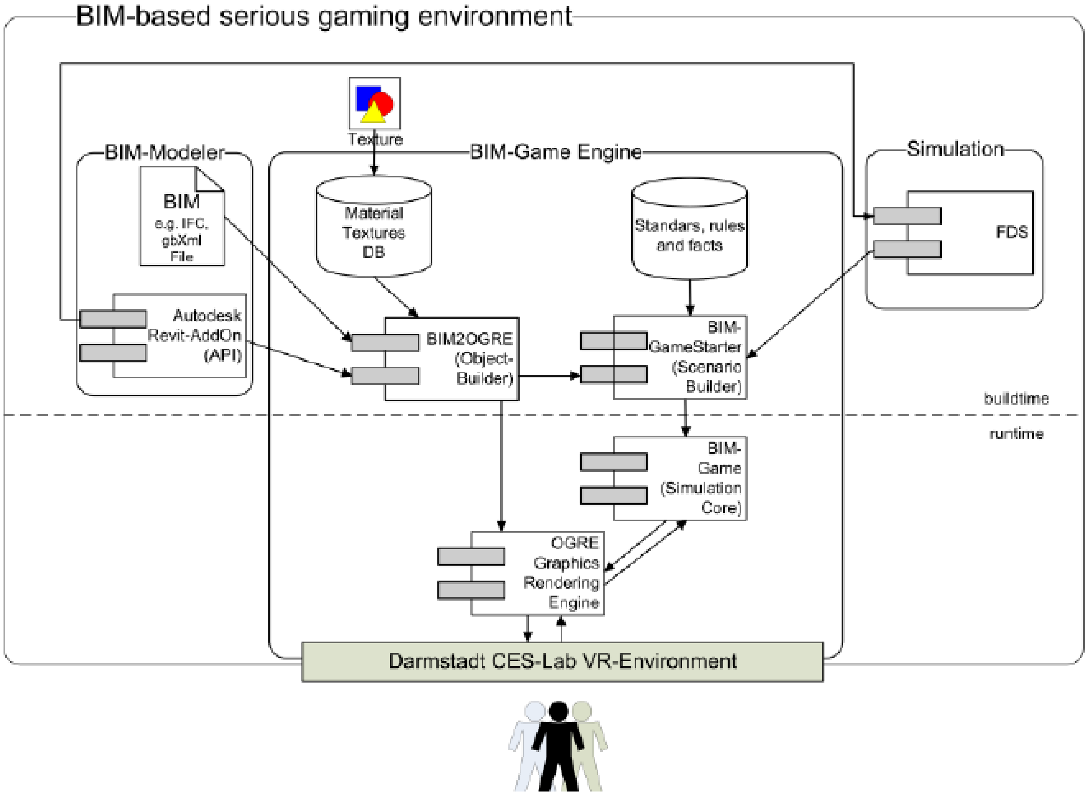


Figure 2.8 BIM-based serious gaming environment (Rüppel and Schatz 2011b)

Torgue: Three main steps were involved for developing BIM-Game workflow based on Torque Game Engine (TGE) (Shiratuddin 2011). Step 1 was modeling of the construction and preparation of the matching textures for all the 3D objects that made up the construction. Step 2 was the placement of all the 3D elements and matching textures into specific TGE data folders. Step 3 involved the assembling of the virtual environment using the TGE World Editor. A summary of the steps is shown in Figure 2.9.

The virtual design review system (VDRS) was developed using the TGE. The VDRS supports VE devices such as the head-mounted-display (HMD), tracking devices, data glove, 3D navigation input devices, game input devices and stereoscopic display (through the use of nVidia's consumer stereo display driver).

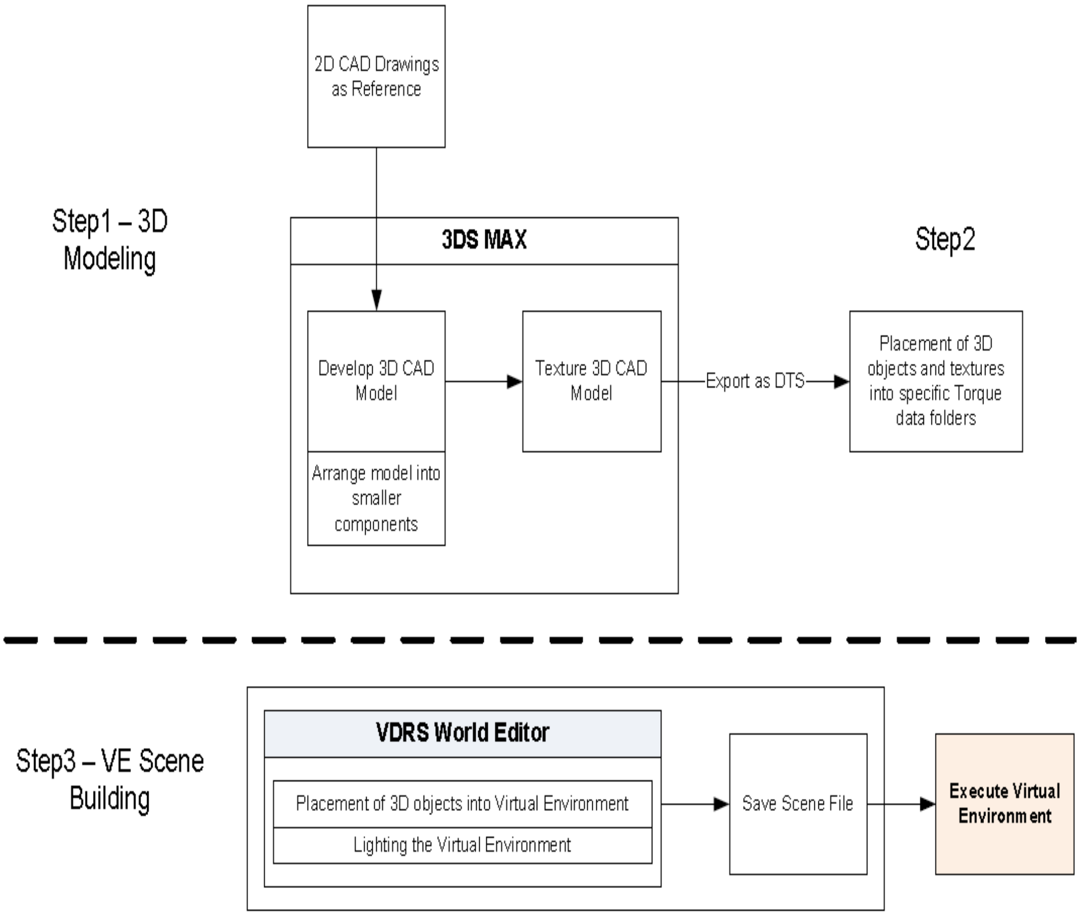


Figure 2.9 The workflow from 3D CAD into the VDRS (Shiratuddin 2011)

2.3.2. Serious game for human behaviour training and research

As mentioned in Section 2.2.1, building emergency management traditionally employs emergency drills or experiments to explore human emergency behaviour with the aim to enhance building safety preplan and evacuation process. However, this method has research limitations with regard to human behaviour in fire, such as resource cost for emergency experiments and the risk of physical danger to participants (Lawson 2011). Another limitations is that participants clearly know they are in a safe environment and do not feel stressed. Some tend to predict possible activities in established scenario according to relative data-collection instead of their instinct response to extraordinary environment. All of these limitations make research reliability of people's behaviours under fire emergency questionable. Then, inaccurate human behaviour research will subsequently influence the success of emergency management for fire. The emergency drill and experiment can only be held after the construction has been completed. It is too costly and time consuming to rectify the building layout if the defect of building design is found.

Fortunately, serious game generated by Game Engine can research and train human behaviours based on individual "human factors" during emergency situation (Rüppel and Schatz 2011a). Serious games can usually be expressed as (digital) games are not only used for mere entertainment but for other purposes such as education, simulation and analysis (Susi et al. 2007; Kobes et al. 2010b). It seems "serious" and "game" are mutually exclusive. Specifically, "serious" plans to reflect the "purpose" of the game (i.e. why it was created) according to Michael and Chen (2006). As for "game", "fun" component must come first. Without "fun", their use for various purposes is questioned (Prensky 2001). Michael and Chen (2006) argue that the main purpose of serious game to learn is of primary importance, and if possible, have fun doing it. More broadly speaking, education can be entertaining since the "fun" is only one kind of entertainment. There is a lot of elements can contribute to the engagement of players. For examples, playing can promote the intense and passionate involvement, rules can generate a rigorous and scientific structure, and goals can motivate players to fulfil their potentials (Prensky 2001; Mitchell and Savill-Smith 2004). The difference between serious game and entertainment game can be concluded as following table (Susi et al. 2007):

	Serious Game	Entertainment Game
Objective	Utilize the model and simulation to solve problems	Get rich experience through the game
Focus	Education, train and learn	Have a fun
Simulation	Take necessary and correct assumption to make sure the simulation is workable and realistic	Simplify the simulation process by some technologies (e.g. by random numbers, time compression, etc.)
Communication	Natural (i.e. non-perfect) communication	Perfect communication without delays and misunderstanding

Table 2.1 Difference between serious games and entertainment games (Susi et al. 2007)

Serious game has become a powerful tool to address the wide range of problems since its adoption in the field of science and up-to-minus modern technologies. For example, game technology (Game Engine), communication technologies (sensors, HMD (head mounted display)) and sciences (computer science, psychology and education) can all be utilized to research emergency human behaviour rather than pure entertainment use (Bernoulli and Glanzer 2008). To mix the virtual and physical world, the five main human senses including hearing, seeing, tasting, smelling, touching should be considered. The immersive factor of virtual environment can also be enhanced by adding audio effects (e.g., crack noise, fire roaring, human shouting and crying) (Rüppel and Schatz 2011b).

Indeed, the augmented reality and simulated environments provided by serious games allow participants to conduct experiments that are impossible to conduct in real world due to safety, cost, and time (Squire and Jenkins 2003; Corti 2006). It is also consistently shown that serious game can promote learning (Eck, 2006). Mitchell and Savill-Smith (2004) stated that serious games can support the development of a number of skills, including analytical and spatial skills, strategic skills and insight, learning and recollection capabilities, psychomotor skills, visual selective attention, etc., and even violent games can alleviate frustration mood. However, it is difficult to draw any precise conclusion from studies on computer and video games because the conflicting outcomes of “serious” and “games”. Moreover, possible negative impacts may appear, including health issues (headaches, fatigue, mood swings, repetitive strain injuries, etc.), psycho-social issues (depression, increased gambling, etc.), and the effects of violent computer games (aggressive behaviour, negative personality development, etc.) (Mitchell and Savill-Smith 2004).

Positive impacts of serious game on human behaviour research and enhancement have been reported by several researchers. Enochsson L et al. found a positive correlation between three-dimensional perception experience from computer gaming and better performance in endoscopic simulation by medical students (Enochsson et al. 2004). In the field of architecture and design, computer game can be utilized to develop students’ confidence and abilities in space modelling and design innovation (Radford 2000; Coyne 2003). Guy et al. indicate that three-dimensional models hold a huge potential in enhancing town planning (Guy et al. 2005).

Experiments conducted by some software for attention training have shown that even the casual experience with computer games improve the attention behaviours of children (Navarro et al. 2003). Other potential benefits of games include improved self-monitoring, problem recognition and problem solving, decision making, better short-term and long-term memory, and increased social skills such as collaboration, negotiation, and shared decision-making (Rieber 1996; Mitchell and Savill-Smith 2004; ELSPA 2006). For example, playing on-line community game develops the ability to find information and solve the problem online (Squire and Steinkuehler 2005). Gamers develop their thinking strategies towards more analogical thinking rather than trial-and-error thinking (Hong and Liu 2003).

The role-playing games have demonstrated its efficiency in corporate training by the mechanism of competitive scoring and difficult levels (Totty 2005). Squire and Jenkins (2003) argue that games can be a powerful way of introducing new concepts and bind disparate period of history. In terms of relationship between gaming experience and driving behaviour, Backlund et al. (2006) illustrate that a high experience in computer games can significantly improve the driving skills of traffic school students.

Another example is Baldaro et al. (2004) who apply violent video game to evaluate short term effects on physiological (arterial pressure and heart rate) and psychological (anxiety and aggressiveness) factors and reveal that there is no effect on hostility measures. Similarly, a survey by Durkin and Barber (2002) showed that there is no evidence of violent game posing obvious effects on measures of aggressiveness. On the contrary, some experiments actually indicated reductions in aggression (Griffiths 1999). Despite the above findings, there is still no conclusive answer to the question of evidence for benefits and potential consequences of playing game. However, Eck (2006) pointed out the subsequent research direction: there is a need for practical guidance regarding how (when, with whom, and under what conditions) to integrate games and learning processes to maximize their learning potential and explain why these serious games are engaging and effective.

According to Wikipedia, main users of serious games are the military, government, medical professionals, school educators and corporation workers while the popular fields of its application lie in the global education and corporate training market. Advantages of military serious game include improving hand-eye coordination, improving ability to multitask, ability to work in a team using minimal communication, and willingness to take aggressive action, foreign languages and cultural training (Michael and Chen 2006). In the future, application areas for the military field would integrate with up-to-the-minutes game technologies such as massively multiplayer online games (MMOGs) and virtual reality training.

Governmental games often focus on various tasks to deal with terrorist attacks, disease outbreaks, biohazards, health care policy issues, city planning, traffic control, firefighting, budget balancing, ethics training, and defensive driving (Squire and Jenkins 2003; Michael and Chen 2006). The scenarios of such government game can easily be carried out repeatedly with changeable degree of severity according to different situation to compare the game experiment results. It also allows fire fighters, police, and medical personnel to perform tasks in virtual worlds rather than real experiments that are too dangerous, impossible, or too expensive to be carried out.

Healthcare games are one of most common serious game. There are a great number of serious games related to physical or mental health (Susi et al. 2007). Physical fitness game utilizes input devices like Wii controller and dance pad to promote physical exercise. Health/self-directed care game teaches the end users nutrition and health skills. Distraction therapy game helps patients decrease pain and anxiety before and during surgery. Recovery and rehabilitation game is beneficial for recovery of certain operation such as increasing motor ability of stoke patient. Training and simulation game can improve surgery performance. Game for diagnosis and treatment of mental illness can be used for diagnosing and treatment. Cognitive functioning game can develop memory and analytical/strategic skills. Control game with biofeedback equipment such as sensors that measure heart rate can train emotional and mental control of human being.

Although the benefits brought by education game is controversial (ELSPA 2006; Michael and Chen 2006), the school educators can get the positive effects of education games in different field, which mainly include developing various human skills like strategic thinking, planning, communication, collaboration, group decision making, and negotiating skills(GEE 2003; Squire and Jenkins 2003). To realize the full potential of games as education tools, some elements should be considered: resources (lack of education equipment, insufficient technical support, time consuming to be familiar with the game, etc.), how to merge the relevance of a game with statutory curricula, difficulty in persuading stakeholders to foresee the potential benefits of computer games, etc. (ELSPA 2006). Similar to educators, workers in corporation can utilize serious game to train their various skills (Michael and Chen 2006), including people skills (e.g. how to perform well within teamwork), job specific skill (e.g. how to use specific software and hardware to finish jobs efficiently), organization skills (e.g., how to manage human resources and time), communication skills (e.g. how to express ideas without aggravating others), strategy skills (e.g. how to set goals and achieve them).

Recently, serious computer games utilizing Game Engine are developing where "real" people can play virtually in their role in certain environment, which may provide the reliable data about human behaviour during emergency situation (Kobes et al. 2010b). The challenge is to combine virtual reality and computer game technology for a new kind of immersive, multiple-viewed, dynamic and interactive environment. Beyond that, the system of a building and its occupants can be regarded as a complex sociotechnical system: there are interactions between the building (technical aspects) and the human behaviour (social aspects) which influence each other. The technical aspects are easier to model and to simulate than the realistic behaviour of involved people because it is based on individual decisions in certain situations.

2.3.3. Summary

Game Engine as a tool can work with other types of software like BIM software, 3D modelling software and image design software that are usually already available at any designer office such as Revit, 3D Max, SketchUp and Photoshop. Many of the Game Engines recognize and import the common file formats produced by these other types of software. JPG, TIF and TGA files can be directly imported, as well as FBX, DAE and OBJ files. For sound design, OGG and MP4 can be directly imported. These BIM-Game prototypes enable augmented architectural visualization that allows the designer to experience a design concept from a human point of view, while walking around or through the design in real-time. This type of visualization has the potential to dramatically improve our understanding of the subtleties and hidden intricacies of a design at an earlier stage and throughout the design process than any of the traditional visualization methods do (Harris and Morgenthaler 2004; Boeykens et al. 2007; Conway 2011; Yan et al. 2011). Used in combination with traditional visualization methods, the designer’s comprehensive understanding of a design has the potential to equal that theoretically afforded by a full-scale prototype of the design. Additionally, BIM-Game prototypes allow users (participants) to get real and immersing feeling within 3D-BIM-models, and then to extend the functionality of BIM software such as human behaviour research (Rüppel and Schatz

2011a; Rüppel and Schatz 2011b).

2.4. Ontology and its applications

In computer science, the term ontology refers to a specific kind of information object or computational artefact. Gruber stated that “For AI system, what ‘exists’ is that which can be represented” (Gruber 1993; Gruber 1995). Computational ontologies formally model the structure of a system, i.e. relevant entities with their relations for purposes. The backbone of an ontology is a generalisation/specialisation hierarchy of concepts, i.e., taxonomy. Studer et al. (1998) defines ontology as: “a formal, explicit specification of a shared conceptualization”, which includes three major aspects: conceptualization, formal explicit specification, and shared information.

Ontology is a formal representation of knowledge as a set of concepts within a domain, as well as the relationships between those concepts. Topic Maps is a standard for the representation and interchange of knowledge, with an emphasis on the fundability of information, which is a form of ontology framework (Ramalho et al.). Although Topic Maps enable the organisation and representation of very complex structures, the basic concepts of the topic maps are relative simple; Topics, Associations, and Occurrences (TAO), as well as the additional concepts of Identity, Facets and Scope (IFS). In Figure 2.10, the Topic Map domain is divided into topic spaces that provide views to those resources, which can be used to navigate, query and access information and resource space composed of databases, XML documents, directory subtrees, and any other file used to represent information through topic-to-topic and topic-to-resource relationships. This partitioning enables individual parts of the topic map to be merged or extended without affecting information resources. Also, information resources can be updated without disturbing the topic map.

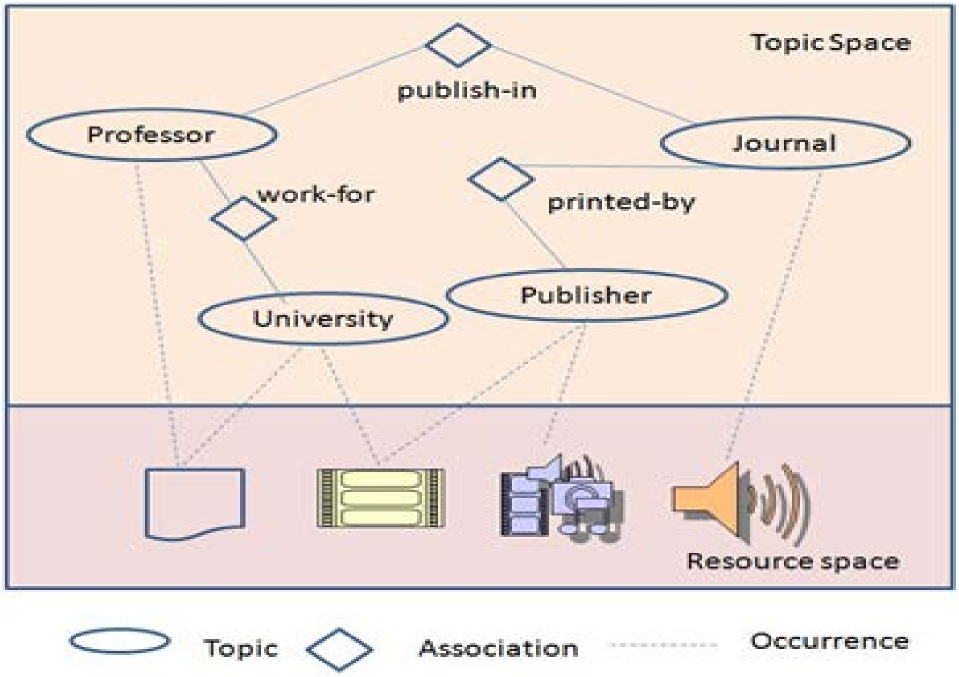


Figure 2.10 TAO of Topic Maps (Kannan 2010)

A Topic Map characterises information using; Topics representing any concept, from people, countries, and organisations to software modules, individual files and events; Associations represent the hypergraph relationships between topics and; Occurrences represent information resources relevant to a particular topic. Topics, Associations, and Occurrences can all be grouped into types, where the types are defined by creators of the Topic Map(s). The definitions of chosen types are known as the Ontology of the Topic Map. This represents the relation between Ontology and Topic Maps. Topic Map is a network of nodes, not a tree hierarchy, representing a collection of topics, associations, occurrences and scope (Kannan 2010).

There are several ontology languages like XML, RDF(S), DAML+OIL and OWL etc. According to (Uschold and Gruninger 2004), the continuum of formal and informal language is shown in Figure 2.11. There is no strict criterion to define the start of formal language. The logic language on the right hand side is usually considered as formal. When choosing a formal language L, we have to balance the expressiveness and efficiency. On the one hand, higher-order logic, full first-order logic, or modal logic are very expressive, but do not often achieve complete sound reasoning. On the other hand, less stringent subsets of first order logic typically feature decidable and efficient reasoning, which can be divided into two major paradigms. The first one from the family of description logics (DL) is strict subsets of first-order logics (e.g. OWL-DL). The second one is derived from logic programming (LP) often uses a syntax comparable to first-order logics. Both can deal with larger sets of data more efficiently than the approach based on first order logic. First-order logic is distinguished from higher-order logics in that quantification is allowed only over atomic entities (individuals but not sets).

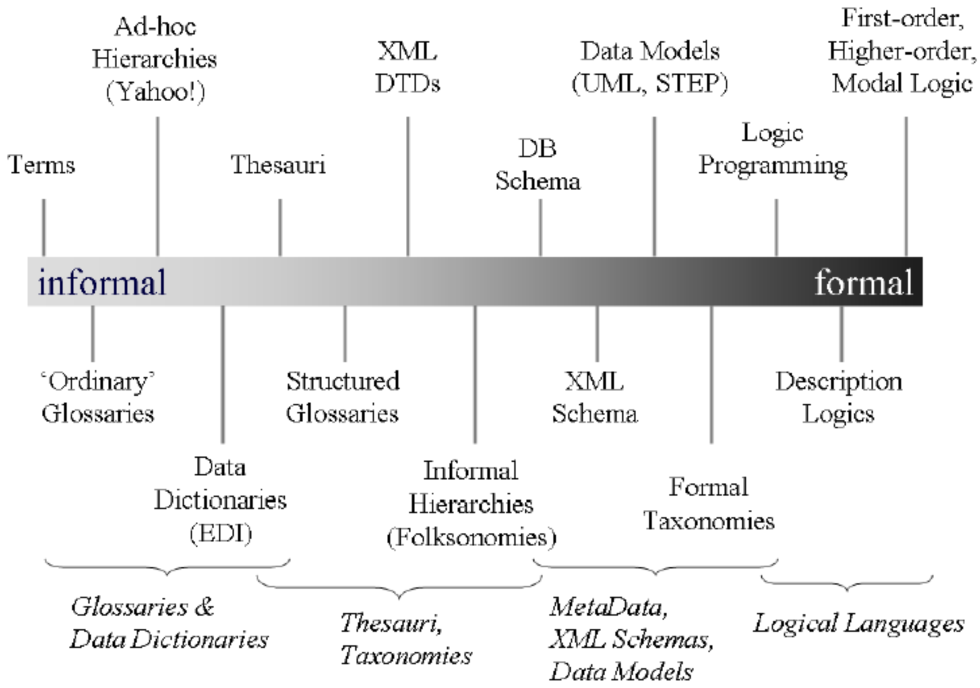


Figure 2.11 Formal and informal ontology language (Uschold and Gruninger 2004)

XML is a popular markup language of metadata. With the development of the XML, different definitions of metadata have been proposed such as Dublin Core and ebXML. However, from the viewpoint of ontology, XML is not suited to describe the interrelationships of resources. Therefore, W3C (i.e. WWW Consortium) has suggested the resource description framework (RDF) and RDF schema (RDFS). The Defence Advanced Research Projects Agency (DARPA), in conjunction with the W3C is developing DARPA Agent Markup Language (DAML) by extending RDF with more expressive constructs aimed at facilitating agent interaction. Ontology Inference Layer or Ontology Interchange Language (i.e. OIL) can be regarded as an ontology infrastructure for the Semantic Web. OIL is based on concepts developed in Description Logic (DL) and frame-based systems and is compatible with RDFS. DAML+OIL Language inherits from DAML and OIL, and combines features of both. In turn, it was succeeded by Web Ontology Language (OWL). Since then, many ontology tools have been developed for implementing metadata of ontology by using RDF, RDFS, DAML+OIL and OWL (Ramalho et al. 2003).

Ontology can separate domain knowledge from the operational knowledge about BIM, game and emergency human behaviour. Consequently it can help organise this crucial information into a reasonable logic and share common understanding of information among people and software agents. The ontology includes structures that allow manipulating terms in a more efficient way; these are beneficial to the human understanding and validation mechanisms operating on inter-agents communication (Rezgui et al. 2011). Thus, Ontology can be used to reason with the entities within that domain, and may be used to describe the domain, which can then contribute to develop artificial intelligence, the Semantic Web, systems engineering, software engineering, biomedical informatics, library science, enterprise bookmarking, and information architecture as a form of knowledge representation about the world or some part of it (Kannan 2010). Better still, ontology enables the reuse of domain knowledge that is created by other domain experts.

In terms of engineering assistive ontologies, Deshpande and Leslie (2011) demonstrated ontology-based software engineering solutions across the Architecture, Engineering and Construction and Facility Management (AEC-FM) industry, which development approaches varied from creating general tools to domain specific decision making system. Elghamrawy and Boukamp (2010) presented a new methodology using RFID framework and semantic ontologies to support effectiveness of construction document information archival and retrieval as well as the efficiency of fusing information for project management. Brandt et al. (2008) advocated the advanced computer science methods that utilise ontology-based schematics with formally defined semantics to capture and reuse engineering design experience.

As for knowledge management and investigation, Beck et al. (2010) utilised the ontology to represent equations and symbols to describe the agricultural model; its potential applications can be models of soil, water, and nutrient management in citrus and sugarcane. This showed that ontology-based approach has advantages for representing complex models that are made up of equations and symbols. Chau (2007) proposed an ontology-based knowledge management system that integrates Java/XML-based scheme, artificial intelligence technology with the conventional hydraulic algorithmic models to automatically generate knowledge search components. Bhogal et al. (2007) reviewed various query expansions using domain-specific and domain-independent ontologies, and applied context from the developed ontology to query expansion within a newswire.

With regard to the internet web, Du et al. (2009) proposed a novel ontology extractor (i.e. OntoSpider) to extract ontology from the HTML Web for other applications such as e-commerce and knowledge management. Baggi (2009) introduced the ontology-based filtering system that allow end users to define XML patterns and ontology queries to extract and exclude XML documents, which can be used through a web application with user-friendly graphical interface. Bittencourt et al. (2009) figured out the challenges of building semantic web-based educational systems (SWBES) with artificial intelligence and software engineering, and proposed a computational model including several ontologies to make the construction of such systems easier and more useful for both developers and authors.

As for e-learning and education, Chi (2009) utilised ontology and semantic rules to describe abstract views of content sequencing and their relationships, which can create durable sequencing knowledge base and a reliable system for an e-learning system. Gladun et al. (2009) presented a Semantic Web technologies-based multi-agent system that allows end users to automatically personalise recommendations and improve the course materials in e-learning frameworks. Sevindik et al. (2010) determined what kind of usage area and described what language a semantic web has in distance education platforms.

2.5. BIM based virtual environment for emergency management

Modern BIM software provides several options to control its output and sound application interface to enable BIM integration with other technologies in different fields for various purposes, which pushes a large amount of feasible extensions to the limits of current BIM development (Conway, 2011, Lertlakkhanakul et al., 2008, Lin et al., 2012). For example, the comprehensive and standardized data format and integrated process enable the BIM based virtual environment to provide better emergency awareness training and up-to-the-minute fire evacuation guidance for acceleration of the fire evacuation process, and investigate fire evacuation behaviour for more accurate evacuation AI. Moreover, with real time building information, BIM based virtual environment holds the huge potential to visualize the real-time building situation for building design and management.

2.5.1. BIM and its information adoption

The basic concept of BIM originated from the late 1970s and early 1980s when one shared digital model was modified and expanded by all parties accordingly (Eastman et al. 2008). BIM aims to make the design more collaborative between the different design parties by using three-dimensional (3D) central models that include both geometric and semantic information. Furthermore, these models provide options and interfaces to control outputs of contained data to other applications and allow smooth interoperability between different software packages (Wang et al. 2013).

Industry Foundation Class (IFC) of the International Alliance for Interoperability (IAI) as a common data exchange format has been supported by most major software vendors within their software packages, and has become the de facto standard for inter-vendor information exchange of building models (Romberg et al. 2004; Plume and Mitchell 2007; Lin et al. 2012). Romberg et al. (2004) took advantage of geometrical information extracted from IFC with p-version (polynomial version) of finite element analysis to perform full three-dimensional structural analysis.

Plume and Mitchell (2007) ran a multiple-disciplinary building design studio employing IFC to support a collaborative design process in a teaching context. When working with a shared building model during the design process, they found operational issues under two broad categories (i.e. building model issues and IFC technology issues) and proposed several strategies to be adopted in future projects. Lin et al. (2012) enhanced emergency path planning using rich semantic information in IFC and the Fast Marching Method. However, both geometric and semantic information defined in the IFC have to be imported into the specific virtual environment manually. It is time consuming and ineffective to manually reimport the ever-changing building information during a fire emergency.

Another way to extract appropriate building information for different purposes is to build an information channel between the BIM model and other systems. This could be done using several methods but one common technology that has be investigated by researchers is that of using Game Engines.

Game Engines are being used to introduce intuitiveness of visualizations, navigation, review, education and simulations in a 3D environment (Ren et al. 2008; Ku 2010; Shiratuddin 2011; Yan et al. 2011). Yan et al. (2011) presented a BIM-Game framework that used a combination of the Microsoft XNA Framework as the Game Engine and Autodesk Revit Architecture as the BIM design application to provide interactive architectural visualization and education, allowing end-users to experience a 'walkthrough' interacting with their own building designs in a real-time, interactive, and photorealistic virtual environment. Although the implementation of this framework provides potential connections among diverse areas such as building modelling, equipment and character simulation and animation, navigation, and interaction through game controllers and use interfaces, its usability and flexibility for those fields needs to be further tested. A prototype where the Torque Game Engine (TGE) has be used to generate a game based building review system has been created by Shiratuddin (Shiratuddin 2011), which allowed the designers to design and edit basic 3D models, communicate with one another and leave notes within the game environment. Nevertheless, the file system they used to transfer building information to a game environment is not automatic. It is very time consuming to manually build 3D environments within the Game Engine based on building information models.

Another area that Game Engines have been used for is that of teaching trainees about construction and fire evacuation skills. Ku (2010) created a game that simulated a construction site, which allowed the user to walk around the site interactively looking for errors, issues and process of the construction site with regards to health and safety. Based on interaction between the users and emergency environments, Ren et al. (2008) developed a virtual system with accurate spreading of virtual fire and smoke to simulate an emergency evacuation within a building. However, the virtual environment used was fixed to a certain scenario resulting in it being too simple to immerse the participants into the virtual education environment realistically.

Guo et al. (2011) used game software 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. Similarly, Harris and Morgenthaler (2004) developed virtual prototyping simulation tools to demonstrate ground processing, depict real-time visualization of design, and plan aerospace missions in a 3-D immersive visualization environment (IVE). Rüppel and Schatz (2011a) have begun to design a BIM-based serious game for fire safety evacuation simulations in the Darmstadt CES-lab. 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 software backbone, 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 could not be updated in real time and was not fully processed automatically. With augmented reality, Koch (2012) 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.

2.5.2. BIM based emergency management

Building emergency management concerns several main aspects, such as emergency preplanning, emergency psychological human behaviour and timely information communication (Kobes et al. 2010a; Gao et al. 2011; Yan 2011).

Emergency preplanning is an action plan devised as a precautionary measure before any disaster and is activated in response to a major incident only. The normal approach to address emergency preplanning includes preplanning drills and digital preplanning (Gao et al. 2011; Lawson, 2011). The preplanning drills are designed to record the behaviours of participants (as evacuees), which usually includes the completion of a post-evacuation 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 (Shields and Boyce 2000; Xudong et al. 2009), With some interesting findings, such as the observation that some exits were not used since there was no staff to direct them there; 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 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 (Lawson 2011).

In terms of digital preplanning, an emergency preplanning semantic retrieval system for facility managers was implemented to retrieve related knowledge from relevant management documents (Hui et al., 2009). Yan (2011) built a core library which can be used to modify, query and match, judge and evaluate, classify and analyse the pre-plans. Through this digitalized emergency preplanning, the end-users can create an evacuation scheme, and monitor the evacuation process in real-time. Nonetheless the above mentioned digitalized pre-plans heavily rely on the complicated database which sometimes can be difficult to maintain and update to a satisfactory level to retrieve meaningful results for the end-user. Rüppel and Stuebbe (2008) combined building information and indoor navigation systems on mobile devices to improve fire emergency plans and route finding for complex buildings. 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, which are available to specific if not all building users.

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 (Purser and Bensilum 2001). 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, a variety of websites, questionnaires, telephone interviews, and face to face interviews (Fahy and Proulx 2005; Technology 2005; Averill et al. 2009). The comprehensive process of data collection mentioned above is time and money consuming and restricted to this specific scenario.

Recent computing developments have enabled computer gaming systems to be utilized for building emergency management. A BIM-based serious game system was designed to explore human behaviour during a fire emergency (Rüppel and Schatz 2011a), but the file system they used to transfer building information to the game environment is only semi-automatic. 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 (Li et al. 2004; Ren et al. 2008). Li et al. (2004) proposed a prototype of a behaviour-based human motion simulation for fire evacuation procedures. Ren et al. (2008) 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. According to Sime (Sime 2001), human behaviour during an evacuation have not been sufficiently understood and require further study to build a connection between the fire evacuation and fire safety engineering. However, questions have been raised about how to precisely represent emergency behaviour to simulate a fire evacuation (Lawson 2011).

2.5.3. Need for BIM-based building monitoring

Traditionally, video cameras and motion sensors are the most common devices to monitor occupants and buildings on large scale. After the terrorist attack on the World Trade Centre (WTC), researchers revealed key factors influencing the success of an evacuation in high-rise buildings based on camera and sensor recordings from the WTC (Gershon et al. 2007; McConnell et al. 2009; Galea et al. 2011).

Recently, Dibley et al. (2012) introduced a software agent system based on building sensors on top of an ontology to respond to the dynamic and changing building environment. Kobes et al. (2010c) proposed that the use of a serious video game to allow real-time observation of the building and human performance might be a promising method to break this bottleneck, because it can employ virtual objects to represent real places in a space sensitive 3D environment.

In addition, a huge amount of data generated by building sensors plays a pivotal role in retrieving insight into building energy utilization and detecting emergency situations (Yoon et al. 2009; Zeng and Tabirca 2009). But the visualization to interpret this data is limited to 2D graphs and numerical outputs, which are too abstract to be fully understood by general end-users such as building owners and occupants. However, the comprehensive and standardized data format and integrated process provided by BIM enables the integration of sensor data within building information models to intuitively interpret building performance for end-users. Indeed, Alahmad et al. (2010) proposed a real time power monitoring (RTPM) system that integrated end-use detailed energy consumption data within a building information model to create an online electronic information model. Costa et al. (2013) also employed the BIM to produce an integrated toolkit to perform building energy monitoring and analysis for energy managers.

2.5.4. Summary

BIM can extend its functionalities by sharing information with other filed software via specific data format such as IFC or an interface to extract necessary information. Although all of this information exists within BIM, many end-users would not be able to understand the raw information and therefore it would need to be presented in an easy to assimilate form. This could be done using several methods but one method that has started to be investigated by research is that of using Game Engines to generate the virtual environment. The virtual environment is being used to introduce the simplicity of control and intuitiveness of navigation in 3D environment for various purposes within the Architecture, Engineering and Construction (AEC) industry.

In terms of emergency management, one of the situation that virtual environment is being applied to is that of simulation evacuation of the population of a building in a situation such as a fire. The generation of the virtual environment is based on 3D information taken from BIM applications. The agent based systems simulates the virtual players attempting to evacuate the building to improve emergency plan. This can be extended and changed from being simply a fully computer driven simulation to one utilising the interactivity offered by the Game Engine to players to identify how they react within the simulation and what decisions they make during such a stressful situation. Such simulations are developing with support of ontology. Another developing area that virtual environment has been used for AEC is that of monitoring building environment, which can help end users detect emergency situation by usual energy usage.

Chapter 3 Methodology

3.1. Systems engineering development principle

In line with systems engineering and agile development principles, the entire research has been devised into 4 parts; review (Chapter 2), system design and development (Chapter 4), system testing (Chapter 5) and analysis of test results (Chapter 6). These four parts follow a research sequence forming up the overall methodological architecture. The review identifies the research gaps, the system design and development, creates expected software platform and realise the required functionalities; system testing section then conduct first hand group using/testing of the developed system against pre-set objectives; and the test results then are analysed and concluded. For each Section, different methods are used to take into account different research characters. Both qualitative and quantitate research methods have been mix-used to achieve the best research outputs (e.g. Chapter 5 and 6); during the system development process, different modules have been designed and developed following several iterations before creating a research prototype for testing.

Corresponding to the research objectives, the necessary and feasible computing hardware have to be created, setup with necessary development software packages and prepared for use. Modern BIM software provide plenty of options to enable BIM integration with other software. To build a bridge between professionals and end users, Autodesk Revit, a representative BIM software, was chosen to transfer its building information in a specific format (i.e. FBX) thought a programmed API to a virtual environment generated by a Game Engine. The major consideration in determining the choice of BIM software was the compatibility of many BIM standards that have been laid out for future development. A further significant consideration was the rich third-party support offered by the software development kit. Taking these two factors into account, Autodesk Revit was selected since it is fully compatible with BIM standards and have excellent third party developer support.

The Game Engine is used due to its intuitive controls and immersive 3D technology to create realistic virtual environments for general end users getting involved in building design and management. Specifically, a Game Engine called Unity3D from Unity Technologies was chosen as the platform to interact between professional designer and the end users because it has a simple object orientated and editor based design system that can import Revit supported data. As one of the most famous Game Engines, Unity3D is characterised by its multiple-platform system support. It is also 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 memory used for any specific application and hence promote its spread. Therefore, the Unity3D Game Engine can develop serious games for a wide-range of end-users (even on the other side of the earth via a web browser) to gather measurable and quantifiable information for research (i.e. enhance quantitative research results). On top of the underlying hardware and software infrastructure, the different modules can be developed, including the key two-way information communication; dynamic scenarios generation; emergency evacuation guides and training; interior design; real time monitoring and their integration.

3.2. Computer game system development methodology

The overall system expected is a computer virtual environment; the approach of Triadic Game Design (TGD) proposed by Harteveld (Harteveld 2011) has been adopted as the starting methodology to guide the system development because the TGD approach specially focuses on the development of computer virtual environment with serious purpose such as virtual guidance and training. TGD indicates that a virtual environment designer has to balance three independent worlds during the system design process, i.e. 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; and the world of 'play' concerns the methods used to reach the objectives in the world of 'reality' and 'meaning'. The adapted TGD based framework for BIM-VE development is shown in Figure 3.1, which illustrates what use-cases and actors are involved and how they can be put together to achieve a balanced virtual environment.

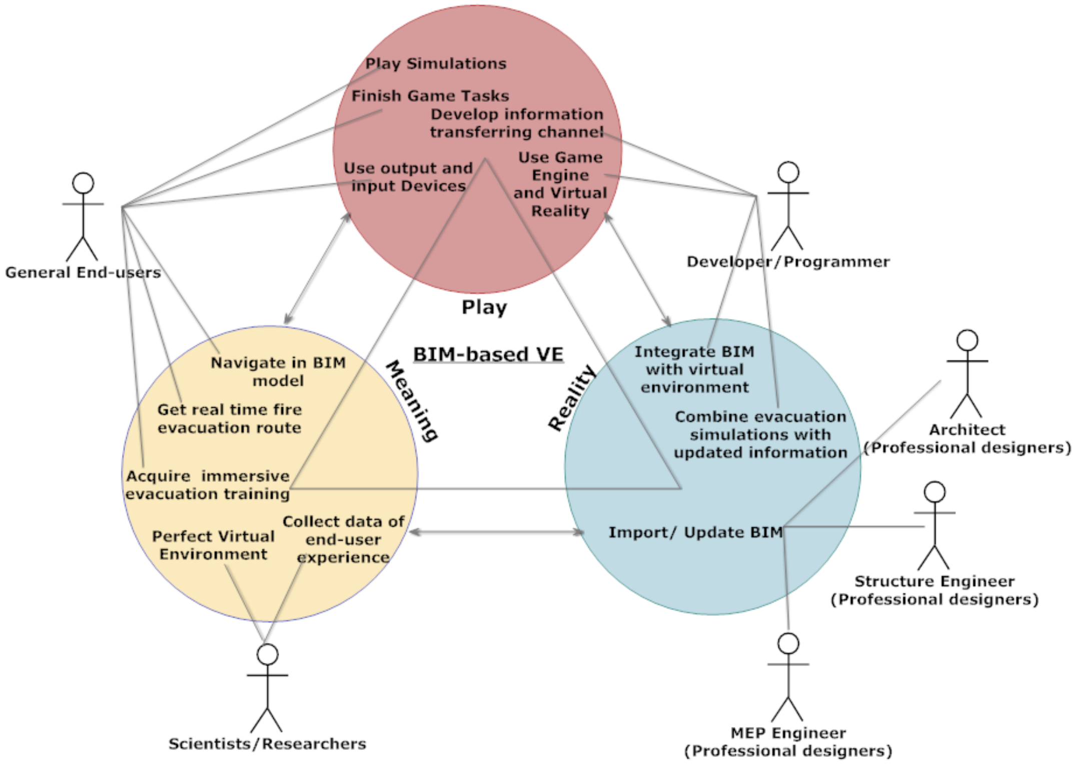


Figure 3.1 Adapted TGD based framework for BIM-VE development

3.2.1. The world of reality and play

Specifically, in the term 'the world of reality', the involved actors focus on how to elaborate the type and details of the virtual environment, depending on domain-specific knowledge from the thematic background of the game. The first challenge for developing the world of reality for BIM-VE is to simulate the real world based on parametric building information (geometry and technical semantic out of legitimate building designs). Previous research (Sections 2.3 and 2.4) has demonstrated how building information models can be used as information provider for architecture visualisation, learning environment, emergency simulation, and human behaviour research. It is possible to directly import building information in specific format into a virtual environment editor to build virtual world (Boeykens 2011). However, this process might take a long time and some parts of building information is often lost. Another factor is that the imported information is often only the geometric building information, without the semantics. Although IFC has become the de facto standard for geometric and semantic information exchange of building models, the results of building information exchanges have not reached a satisfactory level (Lin et al. 2012). Moreover, the complete geometry of a model within IFC was not directly adequate for a numerical simulation because it only described the topology and mutual connections of different structural components (Plume and Mitchell 2007). Thus, further representations of the building's geometry needed to be manually and comprehensively defined.

Another way to build a virtual environment is to build an information channel between building information providers and virtual environment editors (Ren et al. 2008; Ku 2010; Shiratuddin 2011; Yan et al. 2011). However, the previous developed information channel cannot guarantee fully automatic information transferal. It is very time consuming to manually build 3D environments based on a building information model. In addition to that, the developed channel is one-way information transferral rather than two-way between building information providers and virtual environment editors. The virtual environments are fixed to certain scenarios and not flexible enough to be utilised for any virtual emergency testing.

Therefore in this research, the building information modelling is dynamically adopted to automatically build virtual environment for different purposes via a developed two-way information channel. Specifically, the developed system (BIM-VE) utilises a BIM authoring tool (Autodesk Revit) as a building information provider to work with a Unity3D Game Engine to create a dynamic virtual reality environment which can be utilised for both existing and new buildings (Revit and Unity3D is introduced in Section 3.1). The building information updates via a two-way information channel play a key role in simulating the dynamic real world, which is based on an HTTP based AMP (Apache + MySQL + PHP) framework and remote protocol control (RPC) based server-clients framework (introduced in Section 3.2.2).

This research focuses on building emergency planning and evacuation, which needs to filter building information to respond to an emergency scenario as quickly as possible. HTTP based software architecture style includes guidelines and practices for creating a scalable web, which can provide a timely two-way information flow via the internet to respond to the emergency scenario. There are many HTTP based web services (e.g. AMP and REST). One reason AMP system was chosen is because this system is easily adapted to other software. Specifically, there is a free AMP package named 'Wamp Server' that can be installed and configured through any web-browsers with just a few clicks. There are also several existing developed servers that allow end users to work with the BIM model. For example, BIM servers and IFC servers can provide researchers an opportunity to extract building information for various purposes. However, some of these servers are not open source, which make third party development very difficult. Most of them cannot accurately import or choose to import building information from the BIM model for specific purposes (e.g. specific building information for emergency management cannot be chosen to import and some information might be lost during the import process).

The AMP system is open source and provides a flexible medium sized database, which can be easily developed by the third party to connect any BIM packages with virtual environment editors. The AMP system can rapidly manage building semantic information through HTTP protocol and work with FBX plugin (i.e. geometric building information importer) to create a dynamic virtual environment. During this process, the focus is on the data management of a semantic model of a building. In other words, building elements are represented as 3D geometry objects with additional semantic technology information to provide updated emergency solutions in time.

The BIM-VE allows non-professional end-users to assist building design and emergency evacuation planning to achieve user-engaged emergency plan design during all project stages. It can provide effective building emergency management solutions (including emergency evacuation guidance and training) on multiple platforms with virtual reality technology (including desktops, laptops, commonly available mobile devices and web browsers) during and after the building design stage.

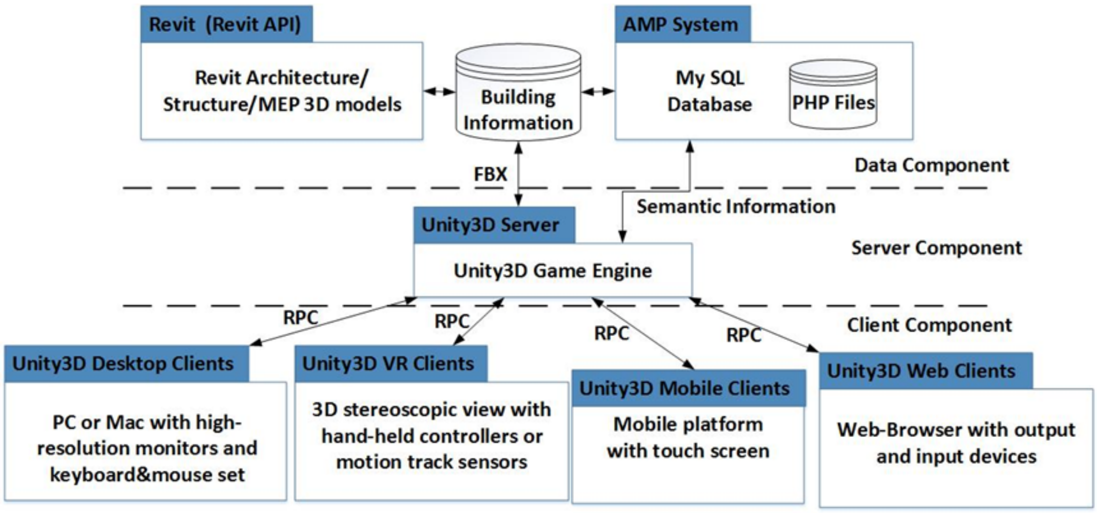


Figure 3.2 System Architecture

The system architecture comprises three inter-connected components (Figure 3.2):

- A data component contains the AMP framework and Revit API. The component is controlled by an 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 research and training.
- A Unity3D server component connects Unity3D clients into an instance and feeds those clients the available data which is created in the data component based on RPC. FBX plugin is used to convert Revit extension to FBX extension that can be utilised to map building semantic information from the AMP system.
- Unity3D clients are the interfaces that immerse the end-users into the virtual environment (as an instance) which is generated by the Unity3D server. Clients work on different platforms with appropriate input and output devices, which allows users to connect to the server through their preferred devices even by a web browser.

Although several recent research studies on fire emergency management have been trying to embed human behaviour modelling into building emergency management, the methods that adequately and precisely represent human emergency behaviour are questionable (Li et al. 2004; Ren et al. 2008). There is still a lack of studies that can conduct effective information interaction between the building and the building user (Rüppel and Stuebbe 2008; Rüppel and Schatz 2011a). However, with the integration of BIM, it can obtain more options to control the inputs and outputs for information interaction, which could be an efficient method to achieve results more representative to real emergencies (Lertlakkhanakul et al. 2008; Conway 2011; Lin et al. 2012). The BIM-VE aims to enhance the virtual environment with simulation of emergency scenarios that is comparable to real fire emergency (e.g. spreading fire, toxic gas/smoke, unexpected explosions) to provide end users evacuation guidance and training as well as researching the emergency evacuation behaviour. The domain-specific knowledge especially from the field of civil and fire safety engineering can help to simulate those reasonable emergency scenarios (e.g. factors that influence the fire evacuation and construction damage). One possibility is to retrieve this knowledge from BIM by using it as “knowledge database”.

Working with the two way information translator of the BIM-VE, the building information can be automatically translated into the virtual environment. However, this kind of translation does not include the definition of factors influencing building emergency design and management. Therefore, BIM-VE introduces a library approach that works with building semantic information to create dynamic emergency factors in the Unity3D server/client end on top of the bi-directional information flow (Figure 3.3) so participants within the virtual environment cannot anticipate scenarios in advance, which will increase the credibility of virtual un-expected emergent events. The library approach, where standard building components can be archived for reuse to create unexpected events, can not only eliminate the time wasted in repetitive data translation and optimisation of rendering parts, but also adds semantic information and animations to enhance the performance of the serious game. With virtual reality equipment, BIM-VE can further immerse users into the virtual environment and utilise the library approach to dynamically generate specific fire emergency factors for emergency training and human behaviour research (Section 3.2.2).

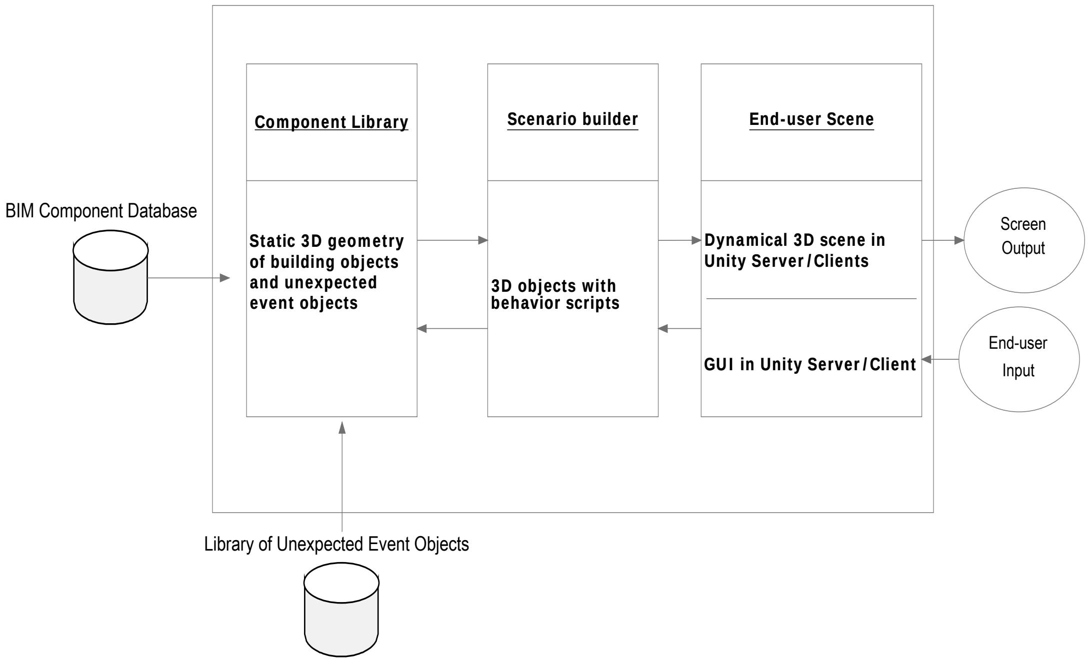


Figure 3.3 The Architecture of Library Approach

Current library functions are divided into two categories: building layout and emergency management libraries. For building layout change, currently basic building components (such as bathroom and kitchen elements) are saved in the library to assist the administrator to dynamically modify the building layout (Section 4.1.5 and 5.2.2). The library appearance and usage is similar for building emergency management, which includes setting up player spawn points, defining the start and end point, adding fire/toxic/smoke, display of people, running unexpected events such as explosions or wall collapses, and activating fire alarms with lights and noise etc. (Section 4.1.3 and 5.2.3).

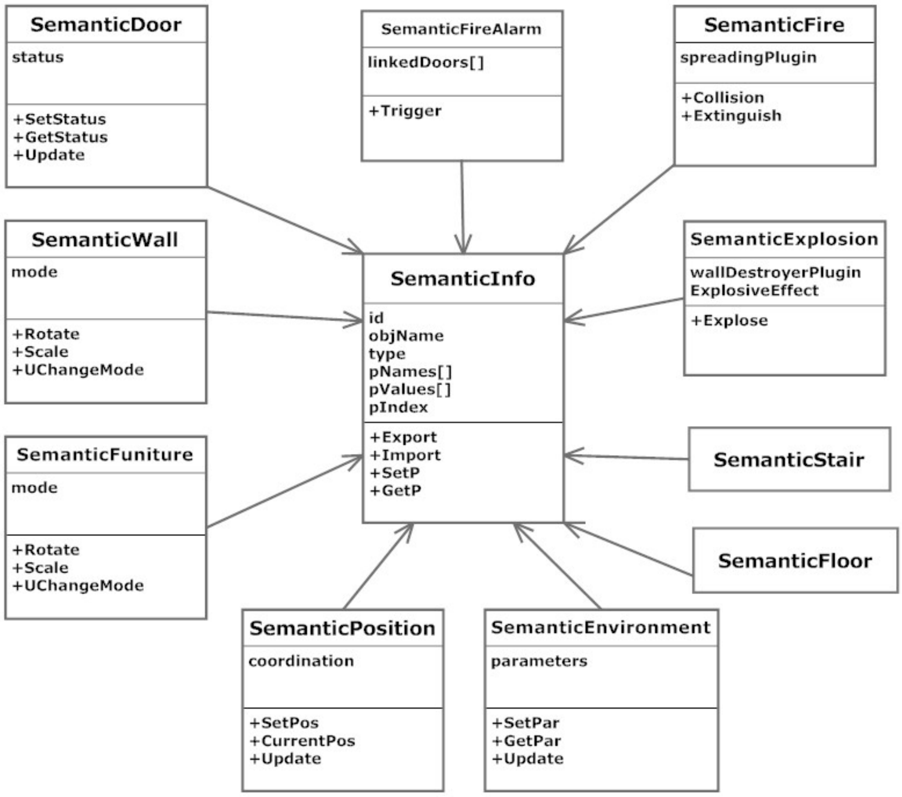


Figure 3.4 Interactive diagram between classes for dynamic scenarios generation

On top of building geometric information, semantic information extracted from a BIM model is utilised to enhance performance of building design and management in the BIM-VE, employing the interactive class diagram depicted in Figure 3.4. The ‘SemanticInfo’ object contains the general properties of a semantic object. Working with it, specific class objects that contain special properties for handling fire emergency evacuation and planning, specifically, ‘SemanticDoor’, ‘SemanticWall’, ‘SemanticFuniture’ and ‘SemanticPosition’ work together to deal with building and furniture object creation, the texture and scale change for building and furniture, as well as the position definition for building and furniture in the scenarios of building design; ‘SemanticDoor’, ‘SemanticWall’, ‘SemanticFireAlarm’, ‘SemanticFire’, ‘SemanticExplosion’, ‘SemanticStair’, and ‘SemanticFloor’ create wall collapses, automatic-shut fire doors, fire alarm activation, expanded fire, and window break events for virtual emergency evacuation trainings. ‘SemanticPosition’ and ‘SemanticEnvironment’ play a critical role in mapping real and virtual building information for building performance visualisation. Note that, the ‘SemanticFuniture’ is the representation for the objects in the bathroom and kitchen libraries and the 'SemanticFire' object is the integration of fire, smoke and toxic gas, which have similar properties, so it is possible to group them into one to simplify the system. 'SemanticStair' and 'SemanticFloor' objects have their own class but are empty now as their semantic information is currently under development for fire propagation. The built-in physics engine in Unity3D 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 the physics performance will be simplified, because entirely correct physics calculations are not the focus of this research but rather only need to "look realistic" for those using the BIM-VE. The simulation in the BIM-VE 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. Additionally, 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.

3.2.2. The world of meaning and play

As for 'world of meaning', Harteveld (2011) suggested that the values involved can include knowledge, skills, attitudes, assessment, data collection, exploration, and theory testing. The values can be divided into two groups: values for players and values for observers/developers. Specifically, players (e.g. general end-users) should be able to navigate the 3D model to get real time fire evacuation guides and obtain knowledge about emergency scenarios. The BIM-VE can be seen as a method or tool to acquire the service and knowledge about emergency evacuation and planning. By immersing a valid model into emergency scenarios, end-users achieve understanding of emergency evacuation process during that moment. Another value the end user should achieve is to train skills that help to survive a fire catastrophe by applying the fire engineering knowledge. An example is to simulate real equipment like a fire extinguisher and allow players to finish tasks in a serious game environment.

If the fire emergency occurs, the BIM-VE can be regarded as the evacuation guide tool which can provide updated evacuation guidance to evacuees on multiple platforms, working with previous virtual evacuation training to enhance real fire evacuation efficiency. Such a serious game can provide useful value to observers and developers of the game such as data collection, behaviour exploration, and building design assessment. If the emergency factors could be properly simulated in the game scenario, it could be possible to assess the player's reaction during a virtual emergency experiment.

The server-clients framework allows end users to achieve the above values. Specifically, the BIM-VE allows end-users to choose their roles (i.e. as an administrator to create a Unity 3D server instance or as a client to connect to the Unity3D server). The various Unity3D clients can connect to the Unity3D server to create a unified network-based platform for user-engaged emergency design and management, while the administrator in Unity3D server controls the functionality of BIM-VE to provide user-centred emergency services to life cycle stake holders. The administrator workflow (on the server side) is shown in Figure 3.5. When the server starts up, the first procedure to implement is to create an instance in the database to store this information. Next it stands by for the semantic and geometric information to load. The loading time is dependent on the amount of building information in the BIM model. The internal process has been conducted to convert BIM data from .rvt format to .FBX format, which buffers at the network layer for incoming clients to load. Finally, the FBX model is loaded into the Unity server and mapped with semantic information for different clients based on the building component's IDs.

The processed data is then sent to clients and rendered on the client side. As the process is asynchronous, the administrator on the server side can begin to calculate evacuation routes (or other tasks, e.g. simulate building performance) according to the updated building information. To reflect the emergency circumstance, the server admin can also set up fire, smoke, explosion and dangerous areas at appropriate locations which are unexpected to the clients. Figure 3.6 shows a generic activity flow on the client side. The clients first need to connect to the server by entering the server IP address, after which the loading of the semantic and geometric data ensues. The clients automatically update the virtual environment and services based on the received building information from the admin.

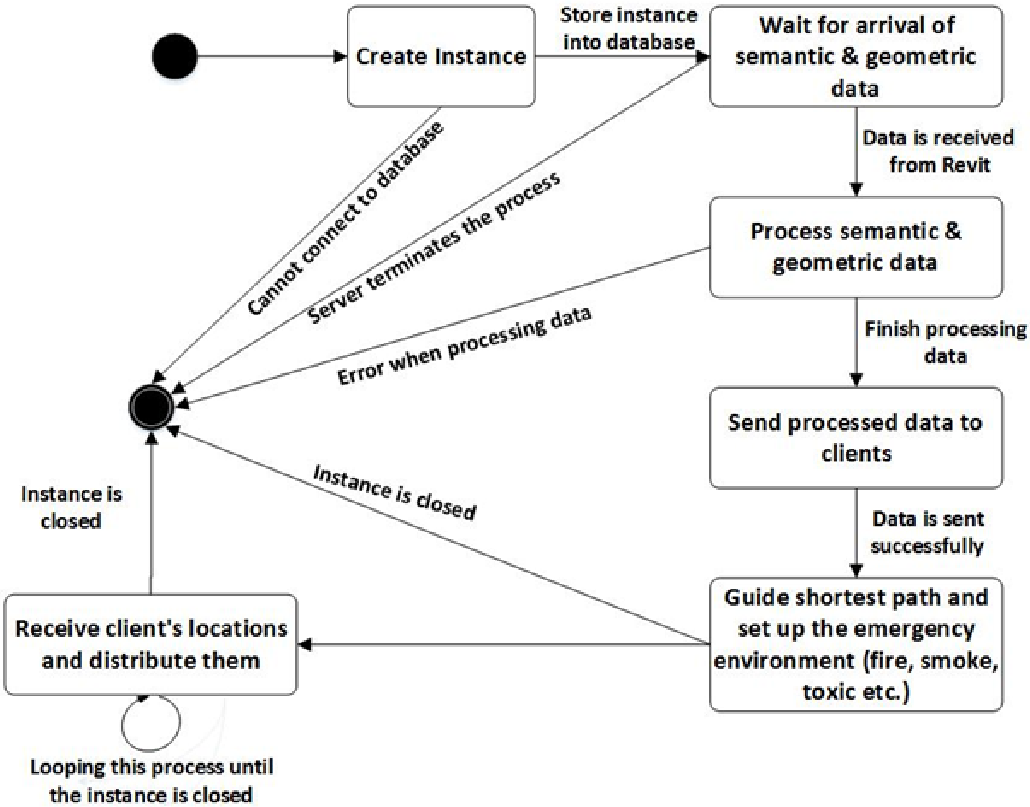


Figure 3.5 Administrator work flow

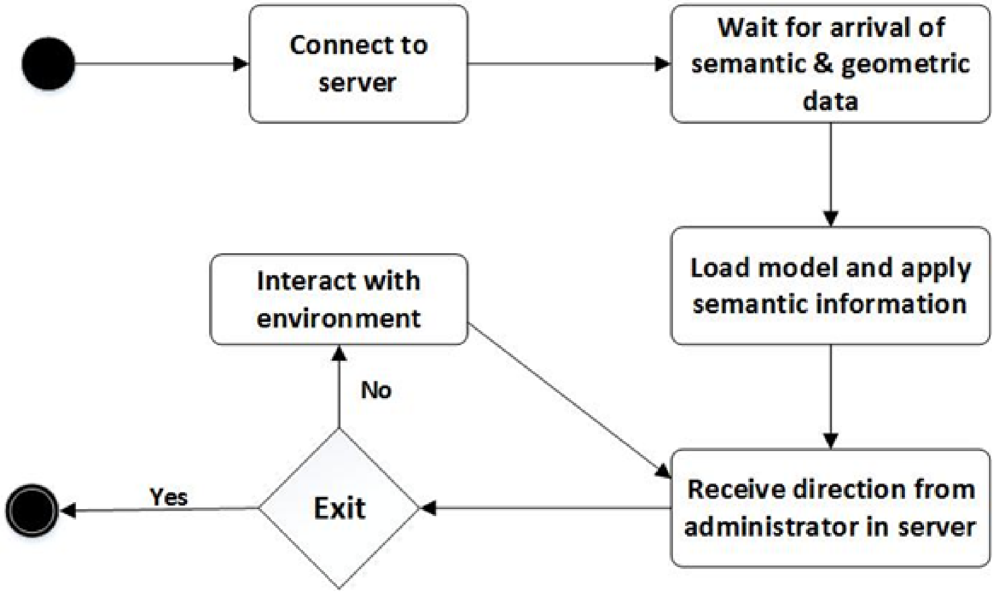


Figure 3.6 Client end work flow

Another aspect that should be considered in the ‘world of meaning’ is the evacuees’ response to emergency situations. These responses are often influenced by emergency factors (Section 2.2.3) that include the nature of fire, human nature, and building characteristics. Especially, feelings and emotions (e.g. fear, hesitation) have to be taken into account when the virtual environment (VE) is generated for virtual training and experiment.

The BIM-VE utilises virtual reality technology to immerse end users into the virtual environment, and further uses the library approach (Section 3.2.1) to show emergency factors to test emergency response of end users. Specifically, the Unity3D Game Engine provides very high quality shading, rendered textures and interface to work with other platforms (including BIM modelling tools and virtual reality equipment). This contributes to making the environment in the serious game comparable to the real environment 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). The information which influences human fire response (e.g. heat, smoke, toxic gas), could be provided by an emergency library in the immersive fire scenario. The player can control the avatar to move though the virtual building and handle objects in the same way as in a real building (e.g., pass doors, avoid fires, or use firefighting equipment).

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 world, the more immersive effects the end users can feel. Suitable hardware for the expression of a VE has been implemented in the Cardiff Virtual Reality Lab, established at the Engineering School of Cardiff University. This 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 includes sight, hearing, body control and smell, utilising both the output of sensory information and input commands from the user (Figure 3.7). Specifically, output equipment 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; a hand-held 3D navigation device such as Wii remote control or Razer Hydro joystick; a 2D navigation device such as mouse and keyboard or a touch pad/phone; and devices that mimick the physical environment such as smoke fragrance and heat radiator.

In order to make end users feel the virtual environment like the real world, the BIM-VE must be able to integrate the sensory output of the environment to the real actions (e.g. 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, end-users in the VE are fully immersed and feel they are actually "present" in the environment, to prevent them from making unrealistic decisions due to a lack of physical attachment to the VE (Barlow and Morrison 2005; Susi et al. 2007; Dibley et al. 2012).

To achieve the above, the following capabilities are needed to immerse the end-users into the VEs:

- High-resolution, 24-bit colour, flicker and ghosting free, 3D stereoscopic display to maximise the visual stimulus of fire conditions (i.e. the 3D projector for group views and the head mounted display (HMD) for better personal view).
- Sound effects should surround end-users to allow end-users to recognise the sound sources. During the virtual emergency environment, it should allow them to locate the emergency by appreciable fire factors such as shouting or crying people, fire alarm, and noise of the fire.
- Motion tracking to use multiple parts of the body (e.g. hands, head, and legs) to interact with the VE and enhance the end-user's physical feeling; It also allows the display of a realistic avatar based on the profile of each user, which can closely imitate their actual movements and physical dimensions.
- Navigation devices that allow accurate direction pointing, fly-through or walk-through in the environment, and manipulation with building objects and allocating new building elements.
- Light source based-rendering and photo-realistic textures.
- Visual consistency (the building elements' position and appearance are predictable like in a real environment).
- Decrease disturbance from virtual and real world.

The virtual environment, based on two way information flow between BIM and Game in addition to server-clients framework between Unity3D server and Unity3D clients, can allow numerous participants to take part in dynamic virtual emergency experiments to explore their fire evacuation behaviour on multiple platforms (i.e. improve quantitative research results), and subsequently embed evacuation modelling into simulations (based on Ontology) to find potentially dangerous evacuation bottlenecks of the building design. During the virtual experiments, data about how emergency factors influence fire evacuation behaviour can be collected. The biometric data of the player such as heart rate or brain activity could also be recorded for research purposes.

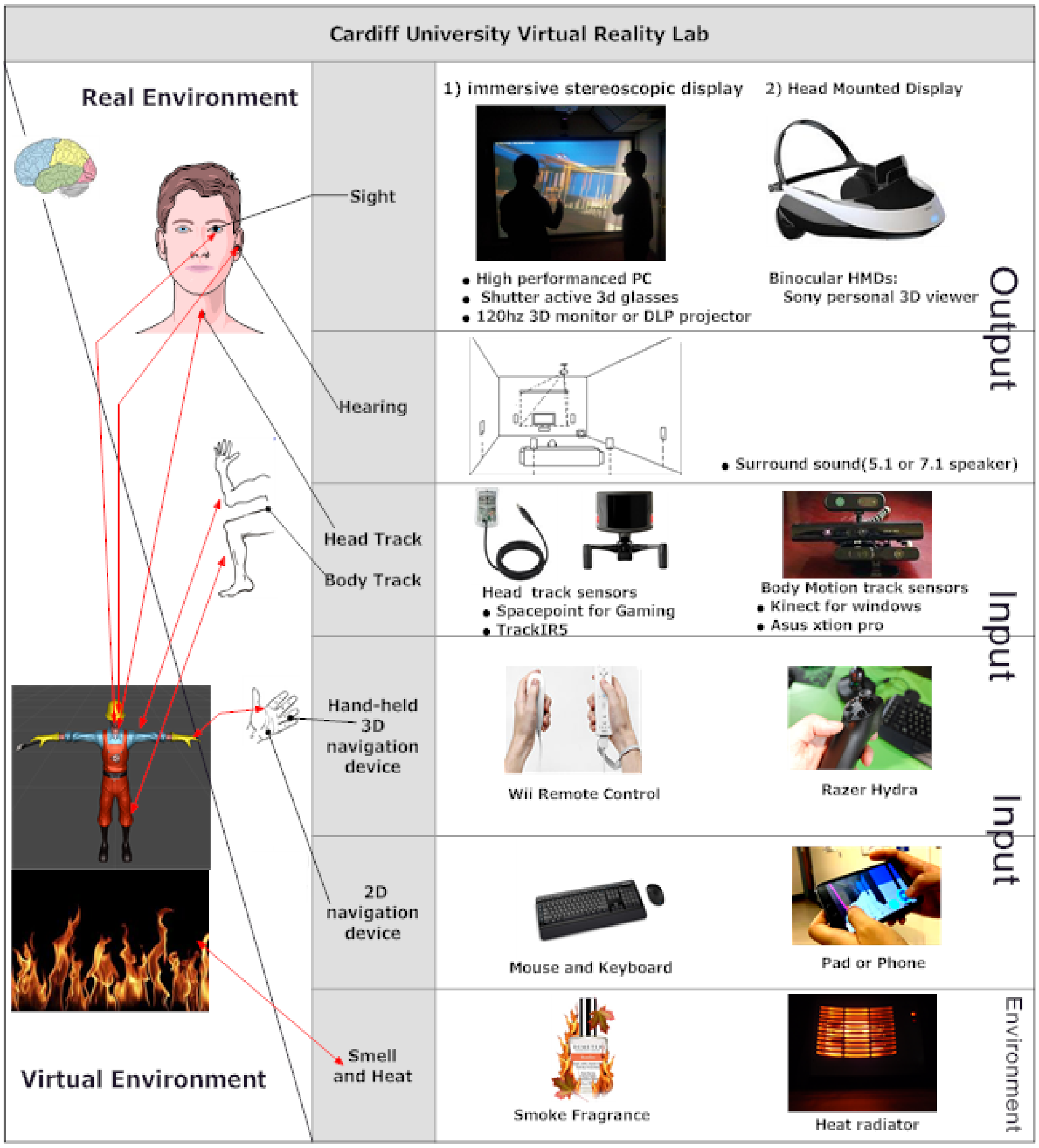


Figure 3.7 Existing and planned virtual reality equipment in Cardiff VR Lab

With questionnaires after virtual experiments, some unobservable human emergency behaviour and questions can be supplemented while the evacuation modelling can be validated and extended for evacuation artificial intelligence. In addition, the questionnaire before the virtual experiments can study personal information of participants, which might find some interesting relationships between individual personality and emergency behaviour.

Harteveld (2011) stated genres of game are very important for the design concept of the virtual environment. He classified them into seven genres: action, adventure, puzzle, roleplaying, simulation, strategy, and virtual world games. The concept of the BIM-VE follows a mix of action, roleplaying and simulation game. According to Harteveld (2011), the action games are fast-paced and the life energy of avatars is limited. The roleplaying games allow players to act a part to finish some tasks in the real world. Finally the simulation game needs to avoid a predefined world and stay close to reality. To achieve objectives defined in world of meaning, the player has to use various input and output devices to play simulations or finish tasks within the virtual world provided by BIM-VE via the two way information channel. The BIM-VE will take up a fire scenario as one possible scenario of a building disaster. For emergency human behaviour research/training, gamers play an avatar with a limited amount of vitality. The aim of the gamer is to guide his avatar through the unexpected virtual fire emergency (dynamically generated by server) to assembly points before his vitality decreases to zero within the virtual world. For emergency evacuation guides/training, the BIM-VE mixes the virtual and real world by virtual reality technology and helps the gamer find the quickest way to a secure area in the real world.

Chapter 4 System Design and Development

4.1. Multi-functional BIM based Virtual Environment (BIM-VE)

4.1.1. Two-way information communication

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 system (Figure 4.1). The data component of the BIM-VE was built of two main components via AMP system: a FBX plug-in '.dll' (application extension) that interfaces with Autodesk Revit (i.e. Revit API) and executable object from the Unity3D server. The AMP system is the central hub to collect and transfer all 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 system. The Revit model is separated into FBX geometric model and a semantic information file. The AMP system then feeds and maps all building information (i.e. geometric and semantic building information) in Unity3D server based on the object IDs of the FBX model. The server component then synchronises building information 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 the AMP system and compares the two semantic information sets to update the appropriate BIM components.

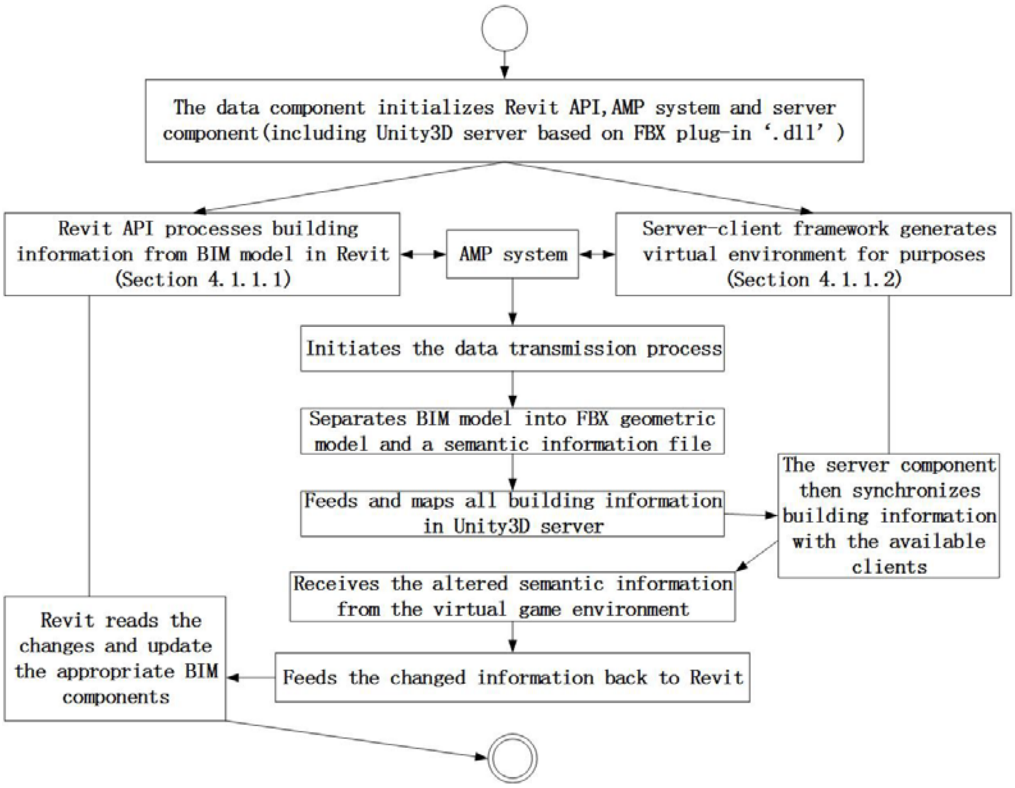


Figure 4.1 AMP system for two way information communication

4.1.1.1. Revit API communicating with BIM model

Figure 4.2 shows the layout of the forms within the Revit plugin and the order in which they appear is shown in Figure 4.3. If end users open a building information model in Autodesk Revit, they can find a ribbon bar button in 'add in' classification of the Ribbon (hidden in Figure 4.2). By clicking the ribbon bar button, the BIM-VE would initiate the Revit API and show the information transferring plugin which includes a server settings form, an information transfer form, and processing information list.

In the server settings form, the end user can set the IP of database host that holds the Unity3D server connecting Revit via an AMP system. Because the Unity3D server with the AMP system can be different for various purposes, IPs can be stored/saved in a drop-down list, which allows the end users choose which Unity server they want to transfer building information to via corresponding AMP system by clicking the 'Join' button. For example, the building information in Revit can be transferred to a Unity3D server via IP recognised by the AMP system (database) for building interior design while they can be transferred to another Unity3D server at the same time for building emergency management (under development).

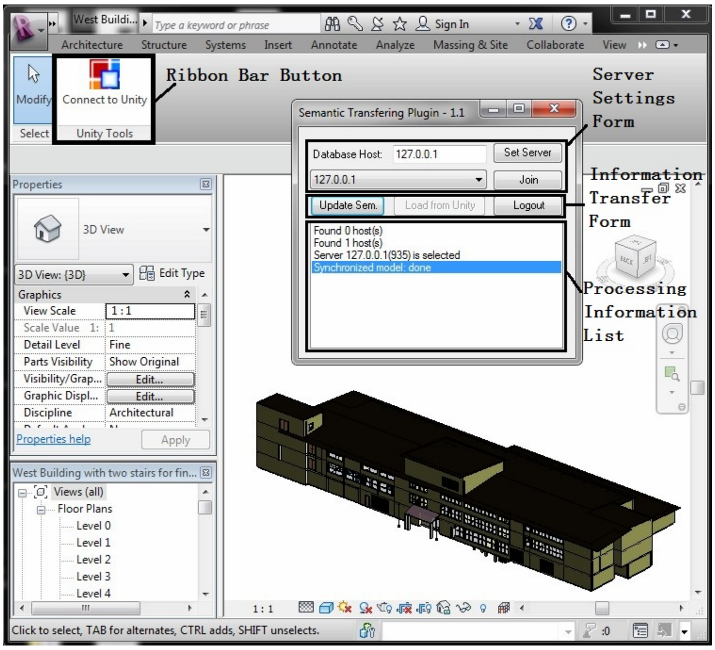


Figure 4.2 The layout of the forms within the Revit plugin

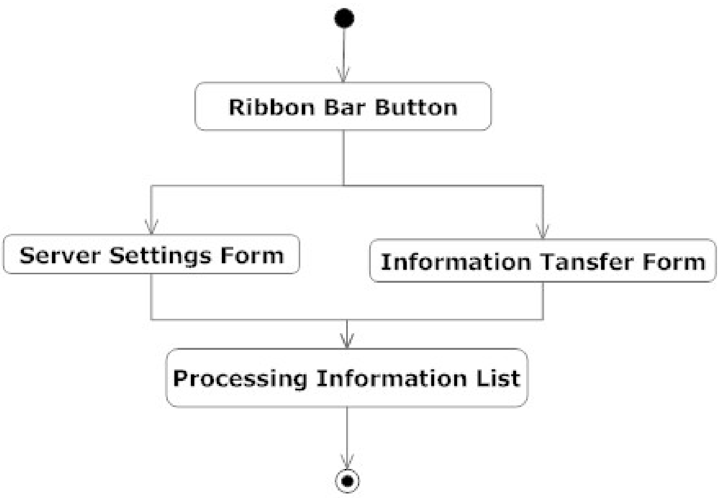


Figure 4.3 The appear order of forms contained in the Revit plugin

By clicking the ‘Updating Sem’ button in information transfer form, all geometric and semantic building information will be transferred to the Unity3D server with unique IP recognised by the AMP system. If there are Unity3D clients connecting to this Unity3D server by unique IP, the Unity 3D server will synchronise building information and emergency guides with connected clients by RPC via network. As for transferring building information from Unity3D back to Revit, the end users can click ‘Load from Unity’, which will automatically reflect changed building information to the corresponding building model in Revit by unique building component IDs. The end users can quit the building information process at any time by clicking ‘logout’. All processed building information above between Revit, Unity3D server and clients are shown in the processing information list.

The workflow contained in the Revit plug-in is described in this Section. The classes of libraries and their functions collaboration that constitute the Revit plug-in are shown in Appendix B. Figure 4.4 shows the basic workflow process that goes on within the plug-in based on relationships between different classes.

When using the Revit API each component has its own functionality to help communicate with BIM model. Therefore, as the additional add in panel (i.e. ribbon bar button), which have been created to initially call the components, the ribbon bar only has one button that utilizes ‘AddPanel’ class library to create all of controls on the ribbon bar when Revit starts up and tells Revit which component is associated with which function.

The ‘RevitUnityInvoker’ class library is used to deal with all of the functionality contained in the plug-in. It is initialised by pushing the ribbon bar button. After clicking the ribbon bar button, the ‘JoinForm’ class initialises label, buttons, combo box, and text box that constitute ‘semantic transferring plugin’. Specifically, ‘JoinForm’ class firstly loads the text tile of Revit API (i.e. Semantic Transferring Plugin - 1.1) and the text of labels (i.e. Database Host), and generates a list to store IDs and IPs of available servers. In order to interact with server, it needs an http protocol interface to request PHP server to obtain available database host IPs. The ‘JoinForm’ class then checks if there is an available server/host IP. If this is the case, it separates the available IPs and IDs from available host list by recognising ‘;’ and ‘,’, then adds them in ‘ips’ and ‘sids’ separately. The ‘textBoxServerIP’ variable store and show these available host IPs in the text box of sever setting form. The ‘JoinForm’ class also stores the processing information in plugin and shows this information in processing information list. In our current implementation, there is only one host can run on a machine at a time, therefore it always return one host which is running on the same machine.

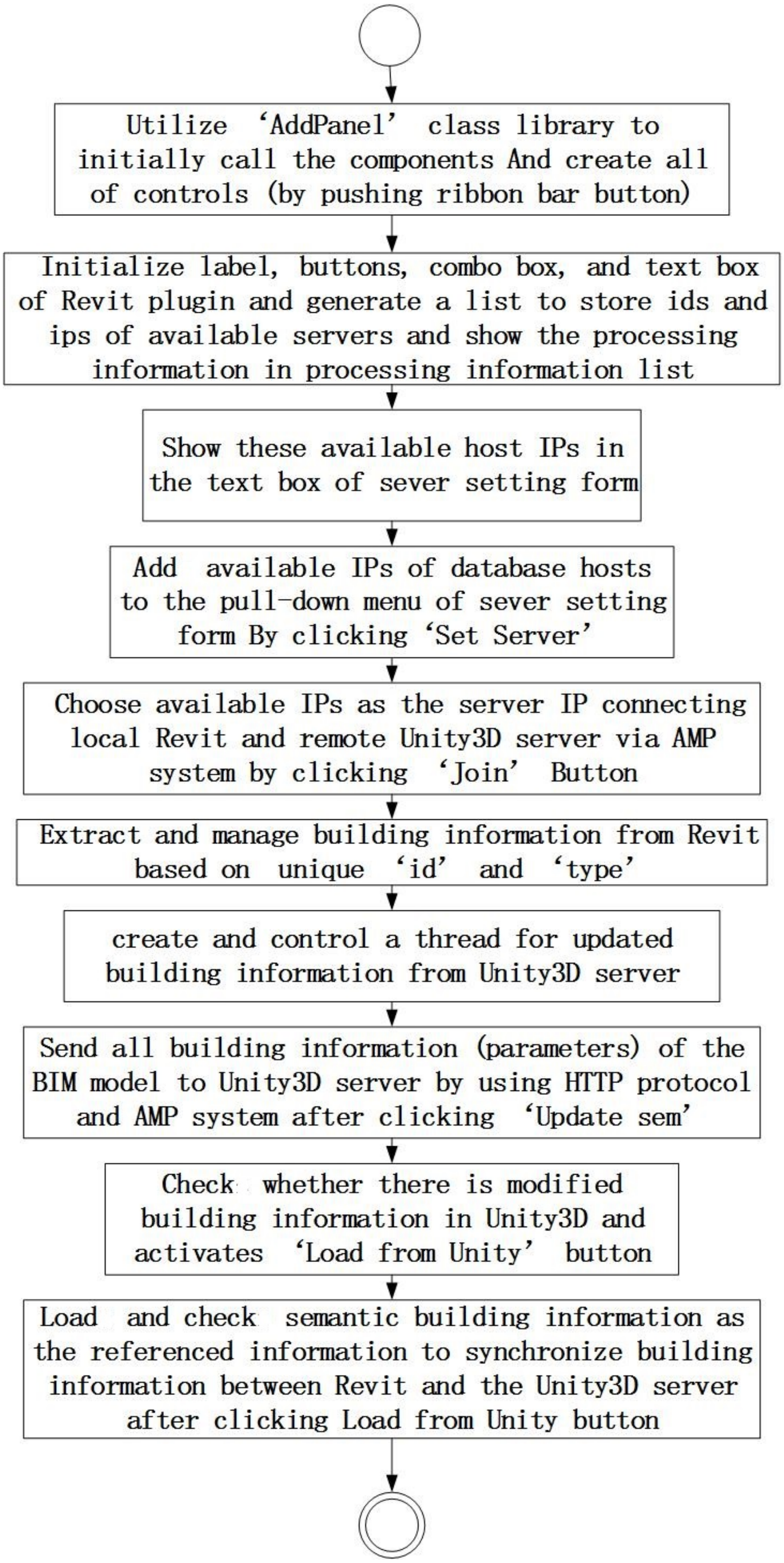


Figure 4.4 The basic workflow process that goes on inside of the plug-in

After clicking the 'Set Server' button, the Revit API adds available IPs of database hosts to the pull-down menu of sever setting form (i.e. stored in the ‘comboBoxServers’ variable), which allows end-users to choose available IPs as the server IP connecting local Revit and remote Unity3D server by clicking the ‘Join’ Button (After clicking the ‘Join’ button, if the end-user does not select available IP/ID or any error makes the selected IP/ID empty, it will show the error message). The reason to do this is because the IPs of database hosts are different in different machines and should be set as different servers for specific aims. During this process, the global variables in the ‘ServiceClient’ class are used mainly to store server IP/ID. The ‘ServiceClient’ class then transfers available host IPs in the ‘textBoxServerIP’ variable with its ‘port’ to set database host. Herein, ‘AppConst’ class includes variables (i.e. ‘SERVER_DB_HOST’, ‘port’, and ‘SERVER_PATH’) to set database host IP, port, and PHP path.

The first step is to extract and manage building information from Revit. The ‘uidoc’ variable of the ‘ServiceClient’ class is used to hold a handle to the current document in Revit. This is so that all of the functions can assess properties and objects in the 3D Revit model. The global variables in the ‘ServiceClient’ class are used to pass building semantic information and the 3D FBX model to ‘SemanticInfo’ class. The ‘SemanticInfo’ class stores the arrays of building information and their names extracted from Revit. Each property is assigned to unique ‘id’ and ‘type’, which ease the process of checking defined items in the property windows of Revit and mapping the properties (i.e. building information value) with their corresponding names. Then, ‘ServiceClient’ and ‘SemanticInfo’ class work together to organise these properties with their ‘id’ and ‘type’, and splits extracted properties with their ids and types in specific format (i.e. name:...;/n id... /n type… /n values… /n) for further processing.

After clicking ‘Update Sem’, the ‘state’ variable in ‘ServiceClient’ class has several decision states such as "joined_server" and "sent_all" to decide whether the process of joining server have been finished and if then send all information to AMP system. Then, ‘JoinForm’ class sends all building information (parameters) of the BIM model to Unity3D server by using HTTP protocol and the AMP system. Due to Revit containing all semantic information of the building design, only the necessary information is extracted which is to be used for the functions of the BIM-VE. Take planning shortest path function for example, object types includes floor, wall, door, windows, fire alarm, marker, ceiling, roof, and obstacle, while properties consist of unique id, floor number of the object, height, volume, width, door status, and marker id number. The ‘component’ variable of ‘JoinForm’ works like a temporary information container, cooperating with ‘Dispose’ method to filter unused building information and dispose of them.

This temporary information container also plays a critical role in transferring information from the Unity3D server back to Revit (after clicking Load from Unity button). Specifically, the ‘ServiceClient’ class checks whether there is modified building information in Unity3D. If there is, it activates the ‘Load from Unity’ button and stores the semantic information in the ‘component’ variable of ‘JoinForm’. Then, the ‘SemanticTracking’ class loads and checks semantic building information (i.e. semantic information monitoring), working with the ‘SemanticInfo’ class to map the modified building information with their name for the information process of two-way information communication. Finally, the modified building information can be loaded from Unity3D to Revit if there is a command from the end-user (i.e. Load from Unity button is clicked).

Specifically, the semantic information can be used as reference information to synchronise building information between Revit and the Unity3D server. For example, doors can utilise their semantic status (i.e. open or closed) to change their geometric position to connect or block evacuation paths. Walls can be shown or hidden 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.

Those above build the two-way information channel. To transfer building information effectively, the ‘UpdateServer’ class works with the ‘status’ variable (i.e. 0 for stop and 1 for running) to create and control a thread for updated building information from Unity3D server. It stores and checks new coming semantic information in different threads because the BIM-VE use multiple threads to accelerate building information processing.

At any time, the end users can log out the current process of information transferal if they click the ‘Logout’ button of Revit API.

4.1.1.2. Server-clients framework for virtual environment

The server component also plays a pivotal role in the processing of the two-way information flow. Revit communicates with the AMP system by HTTP protocol, the server component checks the AMP system every 5 seconds. When information changes are detected on the AMP system, they will be automatically downloaded and sent to Unity3D clients. There is a field named ‘object_file’ in the database to store file names of the objects. The objects are saved in a folder of the AMP system. When the server component requires the AMP system, the PHP will facilitate a download link. The server component bilaterally receives building information from the data component, the Unity server and 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 building emergency design and management. 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 and information 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, avatars etc. Game object management is responsible for creating new game objects with different shapes and add particle systems, camera, GUI, light, wind etc. 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.

With this two way information channel, Unity3D server and clients can work with graphic user interface (GUI) to provide the end-users with emergency evacuation assistant, building interior design tools, and building performance monitoring platform. During design stage, they provide the BIM-based virtual reality environment to immerse building users to the building design and allow them to review and detail building interior design with the help of professionals to achieve user-centred building design. When the building design is constructed, with space searching algorithm and representation, they can further work with augmented visualisation to integrate the real world with dynamic building information to provide building emergency training and real time evacuation guidance on multiple platforms (including desktop, laptop, webpage and mobile devices) if there is a building emergency. To find that potential emergency, they also provide another interface to work with building semantic information and ontology framework to effectively monitor the building performance.

The end users can run the executable Unity3D application via running the main menu of 'serious game' (Figure 4.5). There are two functions which allow end users to choose their roles (i.e. administrator/professionals or general end users). If 'Create Host' button is chosen, the virtual environment in current windows will act as the Unity3D server to synchronise information between the virtual environment and Autodesk Revit, for administrator and professionals for fire emergency evacuation and planning. There is a check box named 'Enable Maintain Mode' besides the 'Create Host' button. If it is checked, the Unity3D server will receive the building information from Revit once and keep this model for next usage, which save transforming and transferring building information to create a virtual environment. However, because the geometric building model is fixed in Unity3D server, only the changed semantic information can be transfer back to Autodesk Revit. This is suitable to provide real time emergency evacuation guidance, which is needed to build virtual environment in a very short time. The suggested evacuation routes can be modified to suit the emergency environment by semantic information. If unchecked, both geometric and semantic information can be transferred back to the Autodesk Revit. Although this may cost more time to transfer building information between Revit and virtual environment, it is suitable to design tasks between professionals and general end users because the building model is often modified by different parties during the design process. Another virtual button named ‘Join Host’ can be clicked to activate ‘connect to server’ menu for general end users in Unity3D clients (Figure 4.6).

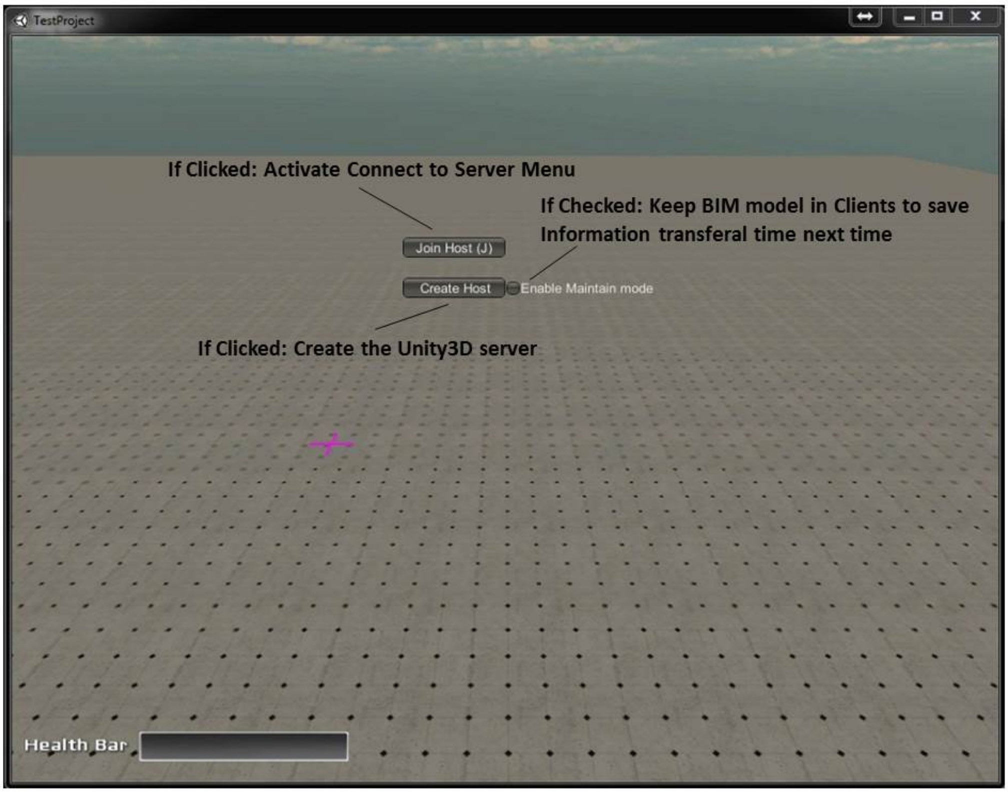


Figure 4.5 Main menu of game

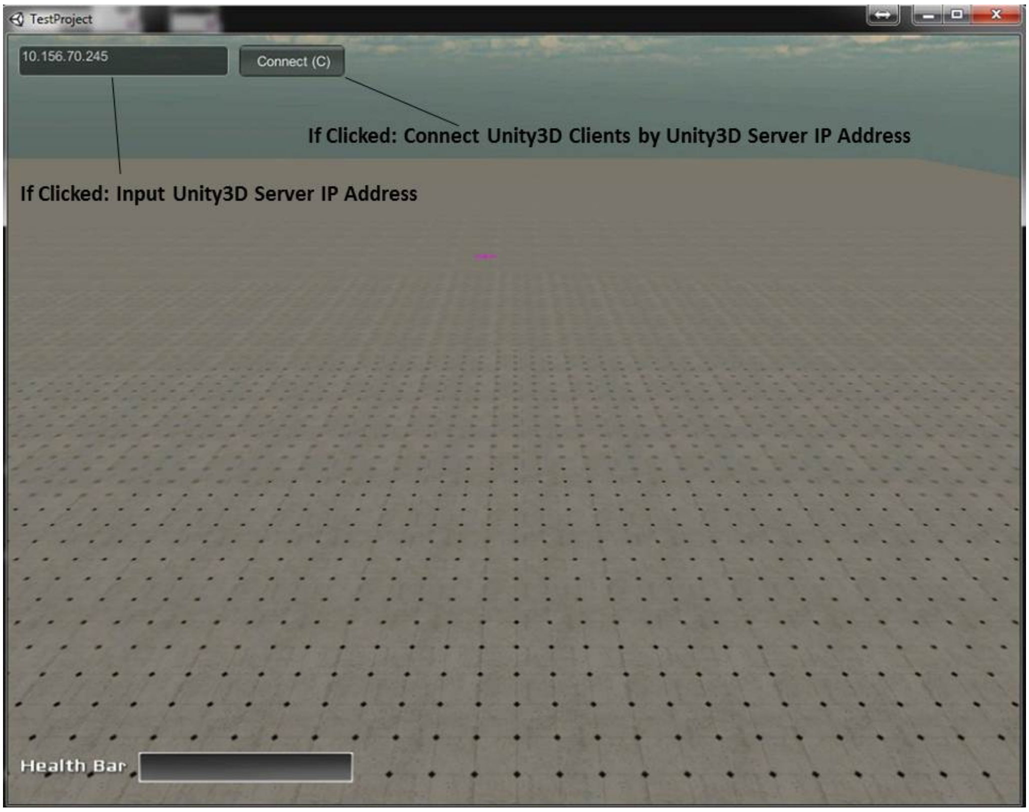


Figure 4.6 Connect to server menu

The general end users in ‘connect to server’ menu can input unique IP address and click ‘connect’ button to connect to corresponding Unity3D server as Unity3D clients. The Unity 3D server receives building information from Revit via AMP system controlled by information transferring plugin, and then automatically synchronises building information with all connected Unity3D clients.

The functionality menu and property windows can pop out in both Unity 3D server and clients (Figure 4.7). Specifically, the end user can use ‘Ctrl’ key to toggle the functionality menu and hover the mouse pointer on building objects to toggle the property windows (showing both semantic and geometric building information). The functionality menus are specially designed for administrators/professionals in Unity3D server and general end users in Unity3D clients. The functions in server can allow professionals/administrator to create the virtual environment for building design (e.g. show tools etc.); carry the appropriate simulation for evacuation guidance (e.g. set started and ended points, switch to multiple path mode etc.); set emergency factors for emergency human behaviour test and training (show effects, set spawn point etc.); and utilise interactive graphic user interface (GUI) to visualise building performance (toggle transparent view etc.). As for end users in clients, they cannot use function menu to create virtual environment and set emergency factors but can still use space searching simulations to find their evacuation way and GUI to interact with building objects.

Figure 4.7 Functionality menu and property windows in serious game

The BIM-VE uses the AMP system and RPC to bi-directionally synchronise building information between Revit, Unity3D server and clients. The workflow of server-clients framework for information transferal and functionality control is shown in Figure 4.8. The whole classes and the collaboration of methods to fulfil above are shown in Appendix B.

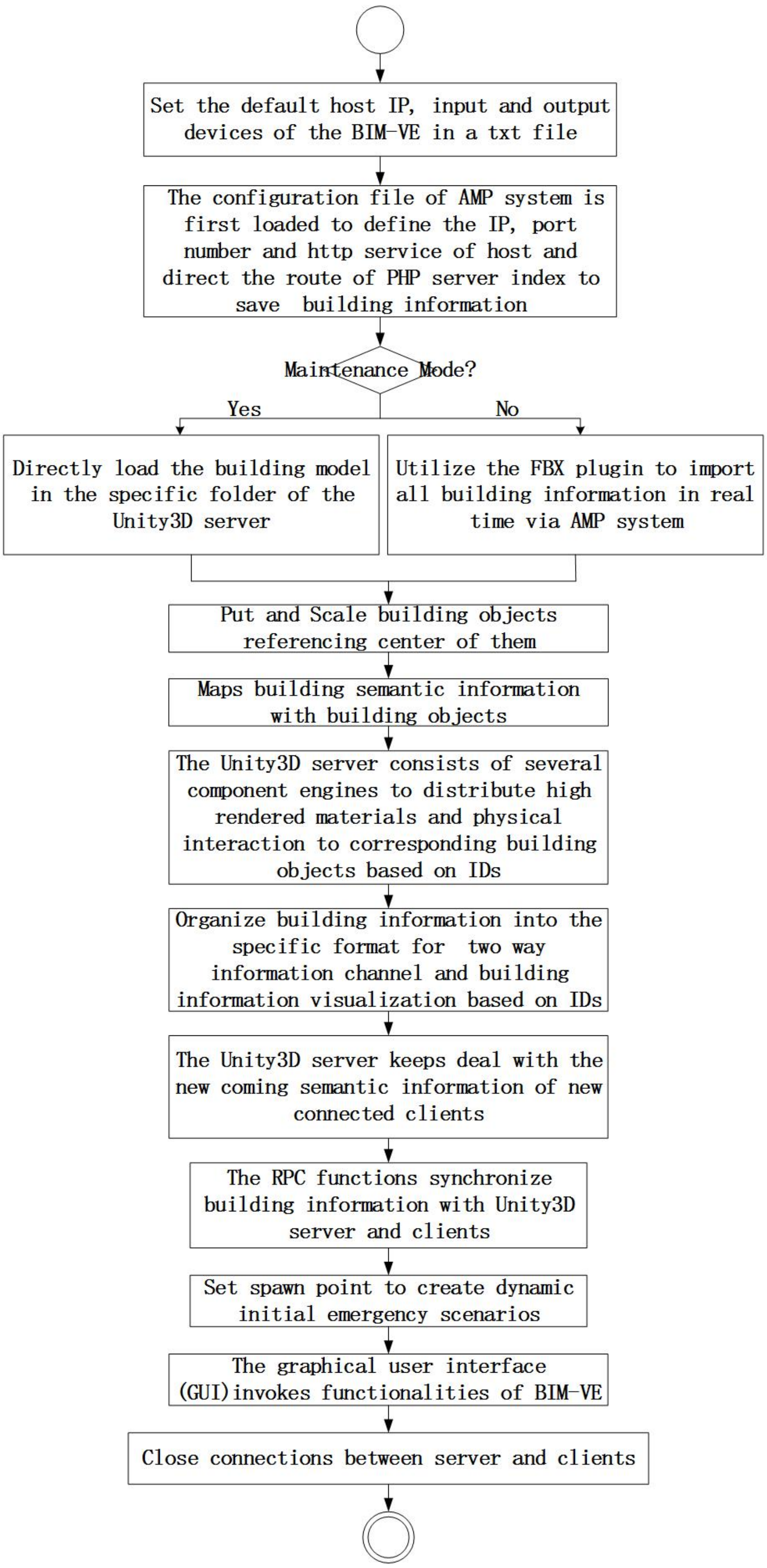


Figure 4.8 The workflow of server-clients framework for information and functionality control

The BIM-VE supports different clients such as desktop clients, VR clients, mobile clients and web clients by various input and output devices, and allows different clients to connect and synchronise with Unity3D server to work on the same platform by unique IP address. Therefore, the BIM-VE allows the end-users to set the default host IP, input and output devices of the BIM-VE in a txt file. During this process, the different clients first judge whether the specific txt file to control the choice of the input and output device is existent. Then, they connect to unique IP address of the server and load their appropriate devices according to their requirements (e.g. virtual reality effect). For example, if 'enable_mouse_keyboard'= '1' (i.e. true/chosen), the 'enable_kinect' = '1', 'enable_touch_pad' = '0' (i.e. false/not chosen), and 'enable_middlevr' = 'config_split' in the txt file, the BIM-VE would use the keyboard or Kinect as the input device, and use the middle VR file named 'config_split' to generate split screen for the activate 3D in the HMD. This enables the combination of different input and output devices to generate the BIM based virtual environment for different purposes. The BIM-VE adds the features of activate 3D plugin to the virtual characters for more realistic feeling such as the box collider on floors and different evacuation animations.

If Kinect with HMD is chosen as the controller devices, the BIM-VE first sets the camera (view) of virtual character using activate3D (for body control) and middleVR (for activate 3D view) plugin within the 3D BIM model. It then focuses on initialising the immersive session such as using depth image of Windows Kinect to control the body of virtual character and the split screen view to generate activate 3D view of HMD for general end-users. The depth capture image of a controller's moving body is shown the image on the top right corner of the computer screen to adjust virtual character moving referencing to the human body moving.

If Razer Joystick with 3D projector is chosen as the controller devices, the BIM-VE allows some actions that can be performed in the 3D immersive environment such as moving building objects or showing real-time building information in the activate3D view for immersive building review and design. It also allows the end-users in the VR clients to define the start point and end point by the buttons of Hydra Razer joystick to support immersive fire evacuation trainings/educations.

If mobile device is chosen as the controller devices and connects to Unity3D server, the BIM-VE enables the virtual wheel controller to tangibly control forward, back, left and right and two buttons to toggle the function menu for real time evacuation guidance or jump the virtual character for virtual evacuation training on the screen of mobile devices.

The AMP system is critical to transfer building information between Unity3D server and Revit. There are also important functionalities within the BIM-VE such as single/multiple path finding, building component editing, and 3D active visualisation etc.

To connect Unity3D server with Revit, the configuration file of AMP system is first loaded to define the IP, port number and http service of host which the clients connect to (i.e. unique IP address), and direct the route of PHP server index to save building information for bidirectional information transfer within the BIM-VE.

The BIM-VE utilises the FBX plugin to import all building information (i.e. both semantic and geometric building information) from Revit to Unity3D server in real time via AMP system if the 'Maintain mode' is not chosen. However, in some scenarios utilising the fixed FBX model such as building interior design or review, the end-users can choose the 'Maintain mode' to save the FBX model in a local folder, which can significantly save synchronisation time between Revit and the Unity3D server.

The BIM-VE checks whether the connection between Revit and Unity3D server has been built via AMP system and organise building information in specific format similar to what Revit plugins do (Section 4.3.1) if the two way information has been built. It then checks whether the fixed model mode is chosen. If 'Maintain mode' is chosen, the Unity3D clients directly load the building model in the specific folder of the Unity3D server to build the virtual environment, which saves the time of transferring building information from Revit to Unity3D server. If 'Maintain mode' is not chosen in server, the Unity3D clients delete the fixed model and downloads building components one by one and maps the building semantic information on the building geometric components via AMP system.

The BIM-VE gets the centre of building objects for putting and scaling them on the appropriate coordination. It organises the semantic information in Revit, and transfers and maps building semantic information with building geometric information in the virtual environment according to requirements of various Unity3D clients. The Unity3D server finally uses several component engines to distribute high rendered materials and physical interaction to corresponding building components based on building objects' IDs and semantic types to build initial virtual scenarios.

Before finishing loading building information, the BIM-VE transforms the semantic information extracted from the Revit property window into the string format that can be utilised by the BIM-VE. It then organises this information into the specific format (with regulated space and number), which ease the way of the two way information channel to bi-directionally synchronise the building information based on the ids of building objects. This semantic information with special format extracted from Revit property windows can also be utilised for building information visualisation within the BIM-VE (by mouse clicking).

The AMP system splits the information in 'status_content' variable with '\n' (i.e. another line) and make sure they meet the format defined in 'SemanticInfo. ParseInfo'. Then, the information in specific format is stored for further information processing. For example, it distributes the index number to the information to control bi-directional information flow. It checks the IDs of indexed semantic information to monitor modified building information (i.e. only defined building components can be synchronised), utilising their indexes to put modified building information to 'content' variable and working with 'sid' and 'syncid' variable to synchronise the changed information back to Revit based on HTTP protocol. Another example is the BIM-VE utilises the semantic information in 'content' variable to show the building object's name, type, floor level, area, volume, length etc. for building information visualisation.

The Unity3D server keeps deal with the coming semantic information of new connected clients. Specially, server component stores new coming modified semantic information in 'status_content' variable and synchronises them with Unity3D server and clients based on RPC.

The Unity3D server can randomly define the spawn points of virtual characters in the safety area to create dynamic initial scenarios for virtual evacuation training/education. The RPC functions are critical in character synchronisation process on all connected clients, which can synchronise character's positions, directions and animation state in the Unity3D clients with their counterparts in the Unity3D server based on character's IDs.

The graphical user interface (GUI) includes how the main menu of game and connect to server menu work together to create the server and clients, and how to show IP address, functionality menu and property windows etc. for various features of the BIM-VE. GUI can also toggle the chat windows to send communicational text and keep the chat history in a chat window between the Unity3D server and clients and for fire evacuation guidance and user-centred emergency design.

If there is a command from the end users, the clients can disconnect from server and the server can close clients' connections to ease information transfer burden. Then, the BIM-VE destroys objects of disconnected clients to keep virtual scenarios clearly understood by general end-users.

4.1.2. 3D Real-time emergency evacuation guidance

4.1.2.1. Path finding algorithm and space representation

Although movement for a single object in the virtual environment seems easy, real time path finding during a fire emergency is a complex process. Consider the following fire evacuation situation: a virtual evacuee initially stands at the start point and wants to arrive at the end point (i.e. emergency exit) in a virtual emergency environment with fires and obstacles (Figure 4.9). If the scan area is small, there is nothing in the area path finding scans (shown in airbrush red line) to indicate that the evacuee should not move toward the walls and fires, heading directly towards the end point; therefore the evacuation path generated by the path finding algorithm would continue on its way, going through the space between the two fires, potentially putting the evacuee in danger. Near the walls, the algorithm detects the obstacles and changes the direction of the evacuation path, which leads to tends to result in the path hugging the walls shown by the black evacuation path to the end point. Therefore, this black evacuation is not optimal for emergency evacuation. In contrast, another path finding method has a larger scan area (shown in light green) of the emergency environment, and finds the shortest path (light blue line), never sending the evacuee into the concave shaped obstacle or the narrow gap between the two fires. However, scanning a larger area for a more effective evacuation path increases the path finding's calculation time, which might delay the beginning of a real fire evacuation and cause subsequent casualties and damage.

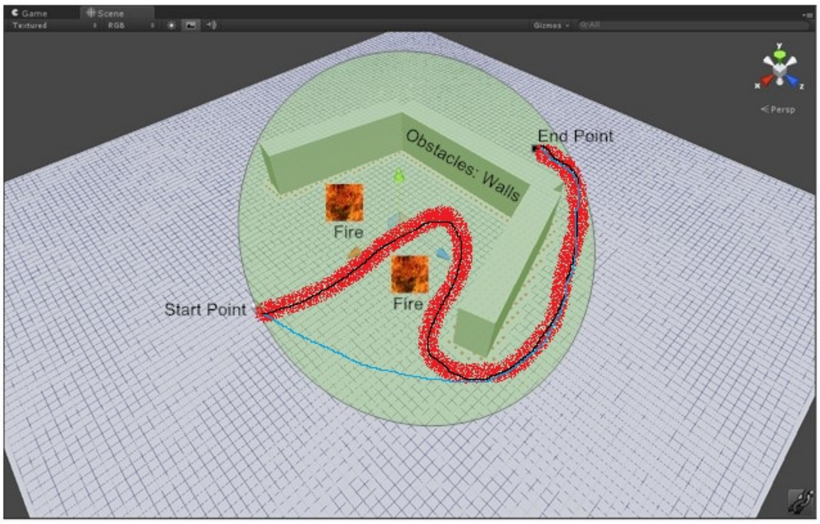


Figure 4.9 Real time path finding scenarios during the fire emergency

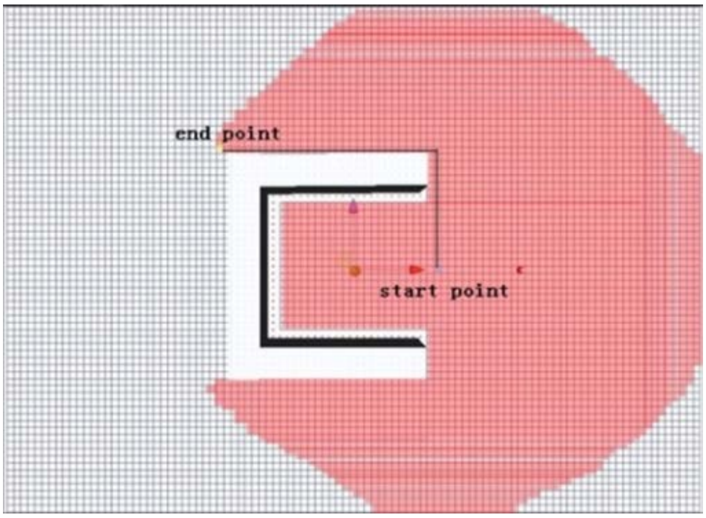
There are some factors that humans consider often, but algorithms do not fully understand such as environment-based movement and time from one point to another point. Therefore, the BIM-VE integrates informative graphs in the mathematical sense—path finding algorithms to generate the shortest path on a set of vertices with edge connections based on the updated building information (Edelkamp and Schroedl 2011). 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 (Patel 2011; Rabin and Sturtevant

2014; Sturtevant 2014).

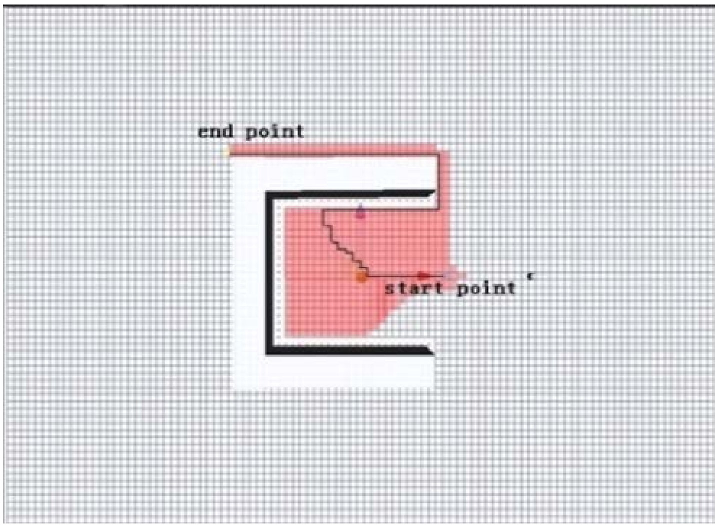
There are a number of standard space search algorithms such as Dijkstra’s algorithm, Best-First search and A* algorithm (Edelkamp and Schroedl 2011). Dijkstra’s algorithm works by adding all the closest not-yet-examined vertices into a representation graph from the object’s starting point to the set 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 (Figure 4.10 (a)). It can be seen that the red dark scan area in the Figure 4.10 (a) is very wide although the algorithm eventually finds the optimal shortest path (i.e. black line) to the end point. Conversely the best-first search has a narrow scanning field but only considers the cost to the goal and ignores the cost of path so far, resulting in the path to goal becoming long and trend to move forward to the wall (Figure 4.10 (b)). It can be seen that the path goes directly towards the end point until detecting the obstacles (i.e. wall) and alters the path. This makes the path longer, although its red scan area is smaller than Figure 4.10 (a). 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 (Edelkamp and Schroedl 2011; Patel 2011), specifically, its knowledge-plus-heuristic cost function of notation x which is expressed as:

$$f(x)=g(x)+h(x)$$

Here, 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.



a) based on Dijkstra's algorithm



b) based on Best-First search

Figure 4.10 The shortest path from start point to end point based on space search algorithms (red area is space search area and black line is shortest path generated by algorithms)

The success of the A* algorithm in shortest path generation is that it integrates space search methodology of Dijkstra's algorithm (Edelkamp and Schroedl 2011; Patel 2011) (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 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. Figure 4.11 shows the black line generated by A* algorithm is the optimal shortest path from the start point to finish but has a much smaller scan area than Figure 4.10(a) reducing computer memory and load.

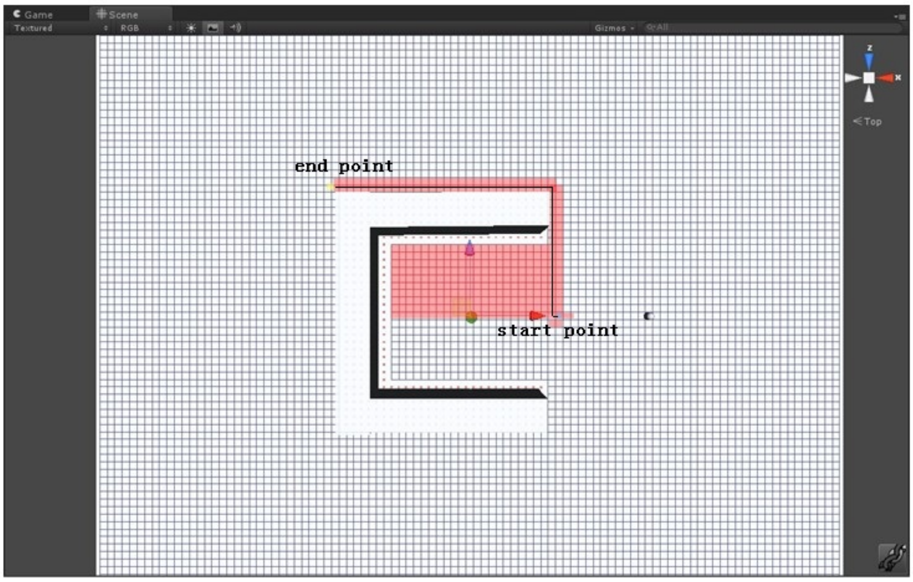


Figure 4.11 The shortest path from start point to end point based on A* space searching algorithms

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 (Edelkamp and Schroedl 2011; Rabin and Sturtevant 2014). 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 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 optimisation 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:

$$f(x)=g(x)+(h(x)\times scale)$$

Where h(x) = $|\Delta x|+|\Delta y|$ (i.e. Manhattan distance)

or h(x) $=\max(|\Delta x|,|\Delta y|)+0.41\cdot\min(|\Delta x|,|\Delta y|)$ (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, 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 the Dijkstra 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 will find 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^o and 90^o are permitted for 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 it can work with a hexagonal grid to provide the most elaborate movement if necessary (Edelkamp and Schroedl 2011). 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 4.12. The black line with many folds 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 with less folds 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 an obstacle between them.

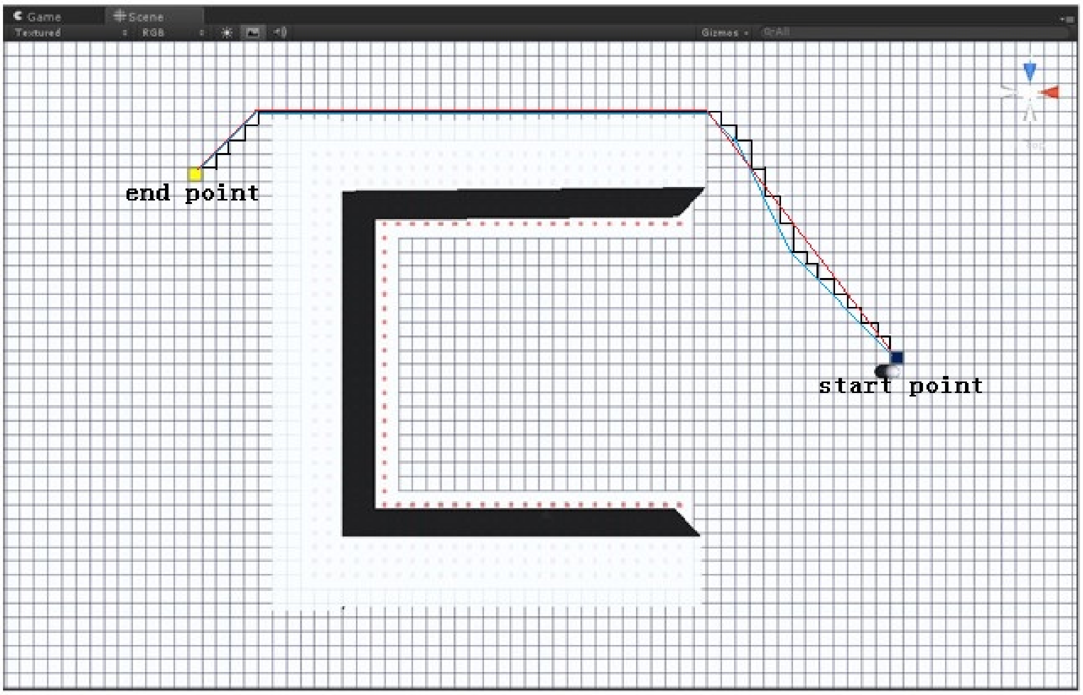
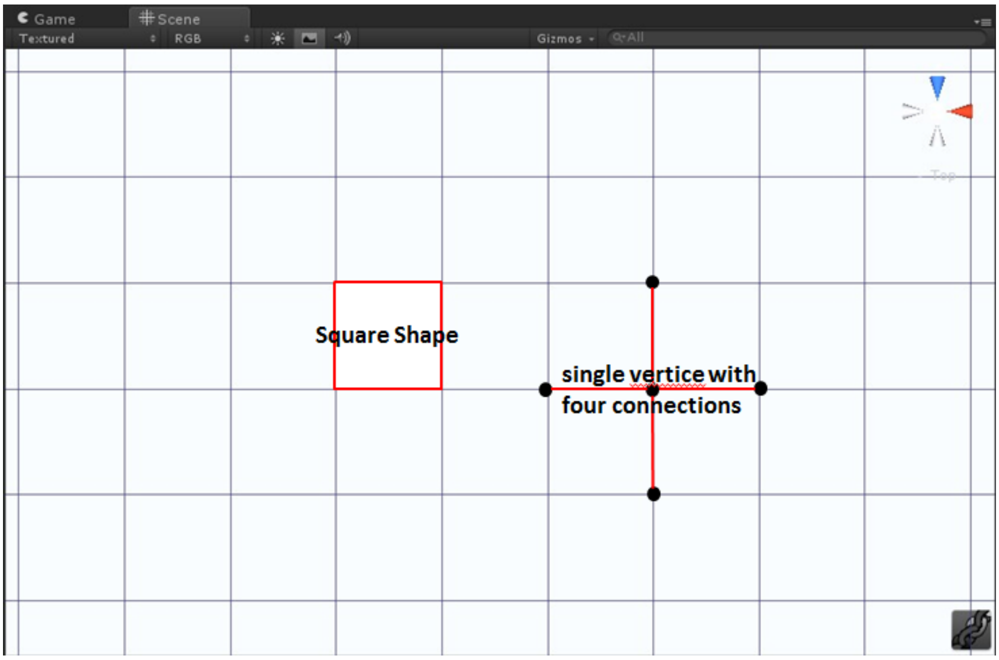


Figure 4.12 The shortest path generated by A* algorithm with different h(x)

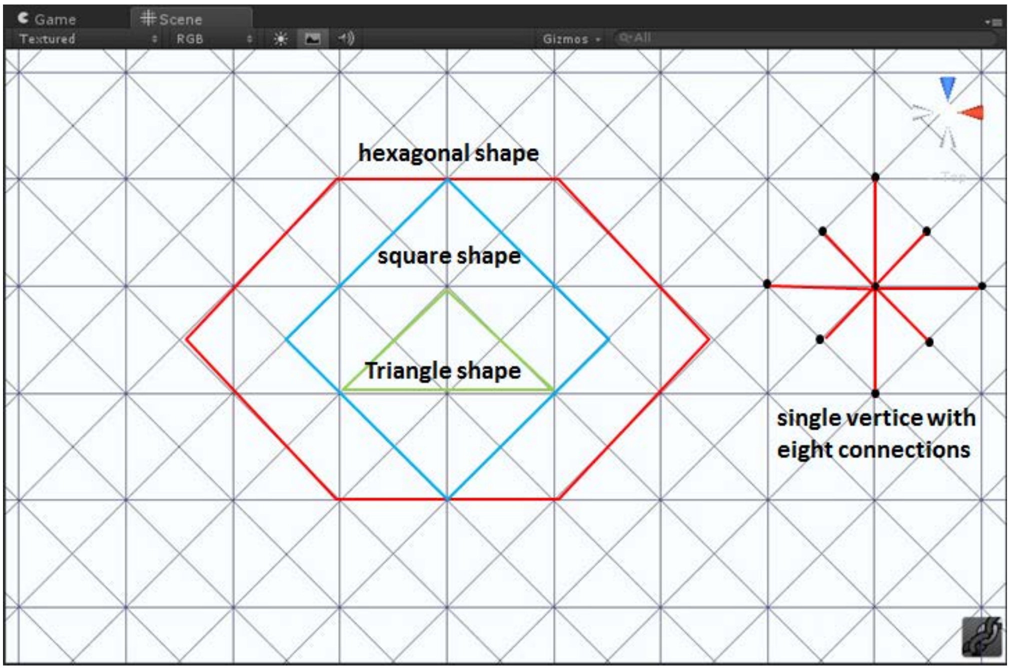
By altering the value of the scale and h(x), it is possible to see how A* behaves to suit the problem, depending on how the complexity of the virtual environment. For example, A* can take Euclidean distance with a relatively small scale adjustment to carry out path finding in a complicated building with narrow corridor and stairs, which can guarantee the A* algorithm to find the shortest path using dense nodes and arbitrary directions. Since the suitable scale and h(x) has 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 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 (Rabin and Sturtevant 2014; Sturtevant 2014). 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 allows the 3D real-time path finding search in the BIM-VE (Rabin and Sturtevant 2014; Sturtevant 2014). Generally, the three main groups of search space graphs are: grid graphs, navmesh graphs, and point graphs (Patel 2011 Rabin and Sturtevant 2014; Sturtevant 2014).

Grid graphs represent the search space by subdividing the world into small regular shapes (i.e. tiles) and generating nodes on the shapes. Common shapes used by grids are triangular, square, and hexagonal (Patel 2011; Rabin and Sturtevant 2014; Sturtevant 2014). The BIM-VE provides flexible connections (i.e. four or eight connections for a single vertices) to balance the shortest path calculation and quality to cover the common shapes that represent the world (Granberg 2014), which are shown in Figure 4.13. It can be seen from Figure 4.13 (a) that a single vertice (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 losses path quality because the path cannot go diagonally. Figure 4.13 (b) shows a single vertice (the black dot) maximally 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 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 (Granberg 2014).



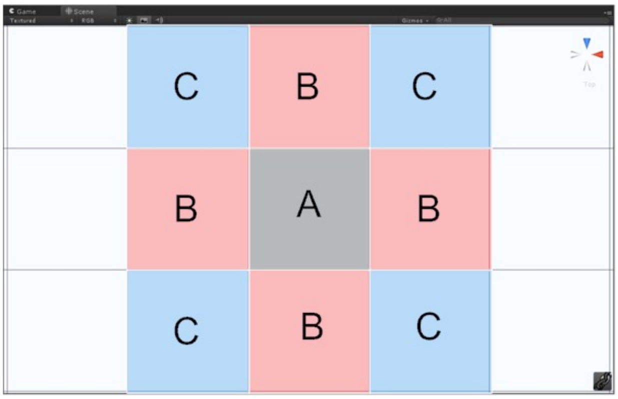
(a) higher path calculation but lower quality



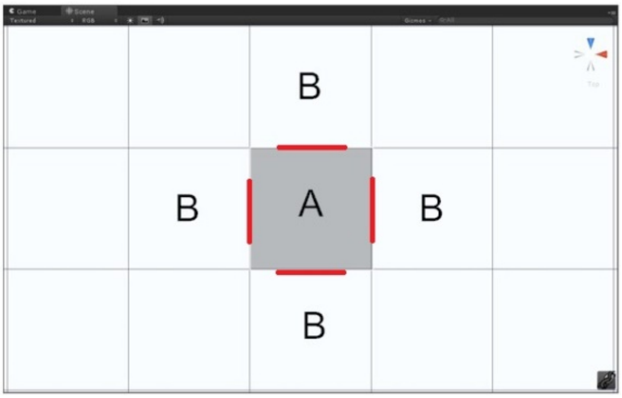
(b) lower path calculation but higher quality

Figure 4.13 flexible node connections to represent common shapes used by grids

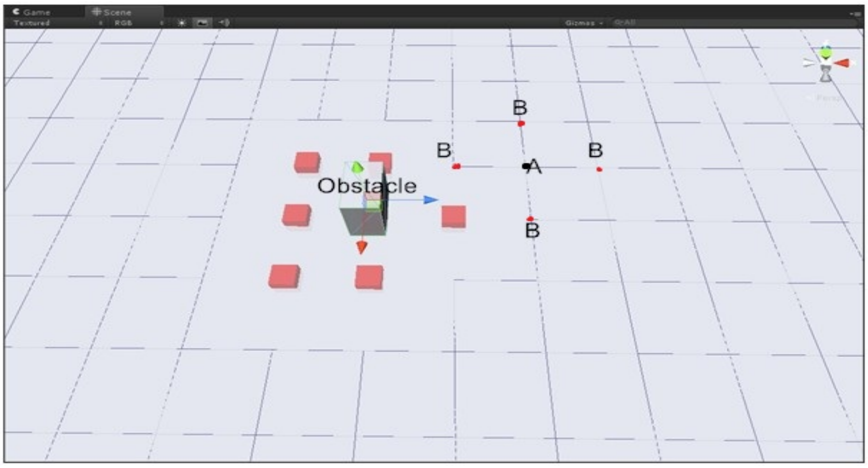
Within grid graphs, there are a choice of tiles, edges, and vertices for the shortest path movement (Patel 2011; Rabin and Sturtevant 2014; Sturtevant 2014). Tile movement is especially useful for the virtual environment in which units only move to the centre of a tile. In Figure 4.14 (a), the unit at 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 vertice 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 4.14 (b)). Obstacles' corners can usually be mapped with vertices of a grid system (i.e. square red dot in Figure 4.14 (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.



a) tile movement



b) edge movement



c) vertices movement (red square dot is the mapped vertices of obstacles)

Figure 4.14 The path movement within the grid system

Navmesh graphs work based on triangles or polygons where each shape covers the walkable surfaces of the world. This generates very precise movement with high speed and low memory footprint as appropriate polygons can describe large areas with very few numbers. Similar to movement within the grid system, the navmesh graph also provides tile, edge vertices or a combination for path movement (i.e. hybrid movement in Figure 4.15). In Figure 4.15, the blue line is the shortest path based on Navmesh graph, contrasting with green, the optimal shortest path. 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. The major disadvantage of connecting every pair of obstacle corners (i.e. mapped vertices of obstacles for path movement) on a Navmesh graph is that the number of move edges will increase to N*N if there are N corners (Patel 2011; Rabin and Sturtevant 2014; Sturtevant 2014). Every solid and dash line in Figure 4.16 can be used to generate a path, although there are only 24 corners in total. The complexity of hybrid movement would be more intensive. Compared to grids, these extra edges can greatly speed up shortest path finding, but they primarily affect memory usage, especially when the space information changes.

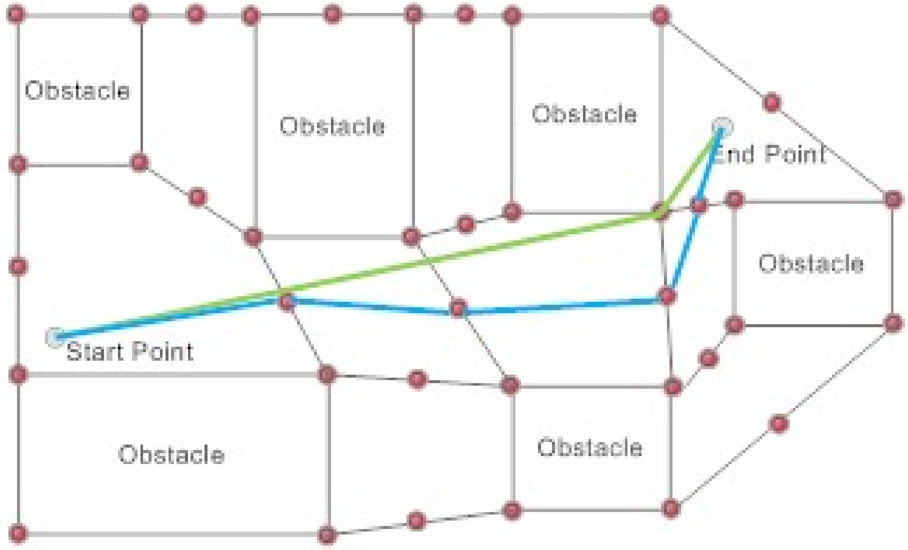


Figure 4.15 Hybrid shortest path generation based on navmesh graph

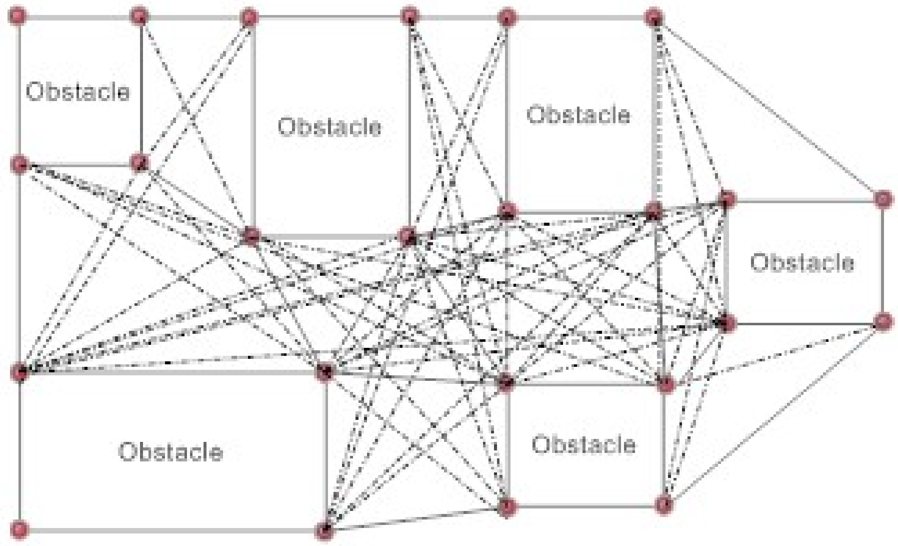


Figure 4.16 The complexity of vertices movement on the nevmesh graph

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 customisable 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 optimised. Worse still, if the space information is changed, the user-placed points must be manually modified to avoid unrealistic path results (Patel 2011; Rabin and Sturtevant 2014; Sturtevant 2014).

It has been shown that an A* algorithm working with a grid graph representation can quickly find the shortest path during runtime (Cui and Shi 2011; Granberg 2014). This begins with representing the world in a grid coordinate system. Take a digital Cardiff city that is created in Unity 3D for example, the world is first divided into small square grids with corresponding tile coordinates. The next step is to define workable tiles (transparent tiles), obstacle tiles (red colour tiles), the start tile (A) and the destination tile (B) according to collected information from the digital city model (Figure 4.17). There are different heuristics for A* path finding algorithm in the BIM-VE. Take simple Manhattan distance for example, because the heuristic estimation for Manhattan (i.e. h(x) that is expressed on the bottom right corner of the tiles in Figure 4.18 cannot go through the diagonal, its estimation cost will become the sum of all horizontal and vertical cost from the current tile to its destination B. It is assumed that both horizontal and vertical tile move would cost 1, and the diagonal tile move would cost 1.4. Then, the A * shortest path finding based on lowest f(x) is demonstrated in Figure 4.18. From the start tile A, the A* algorithm searches all adjacent tiles (shown in blue colour) and chooses the tile with lowest f(x) (i.e. f(x) = g(x) + h(x), shown in green on the adjacent bottom right) as the first tile to build the shortest path to B. Then, it takes the first chosen tile to repeat the searching process until it arrives at the destination tile B. The shortest path from A to B is shown on green tiles in Figure 4.18. By setting the time interval to re-define the world and repeat the whole searching process, A* algorithm can timely respond to changing world information to generate the real-time shortest path on the grid within the BIM-VE.

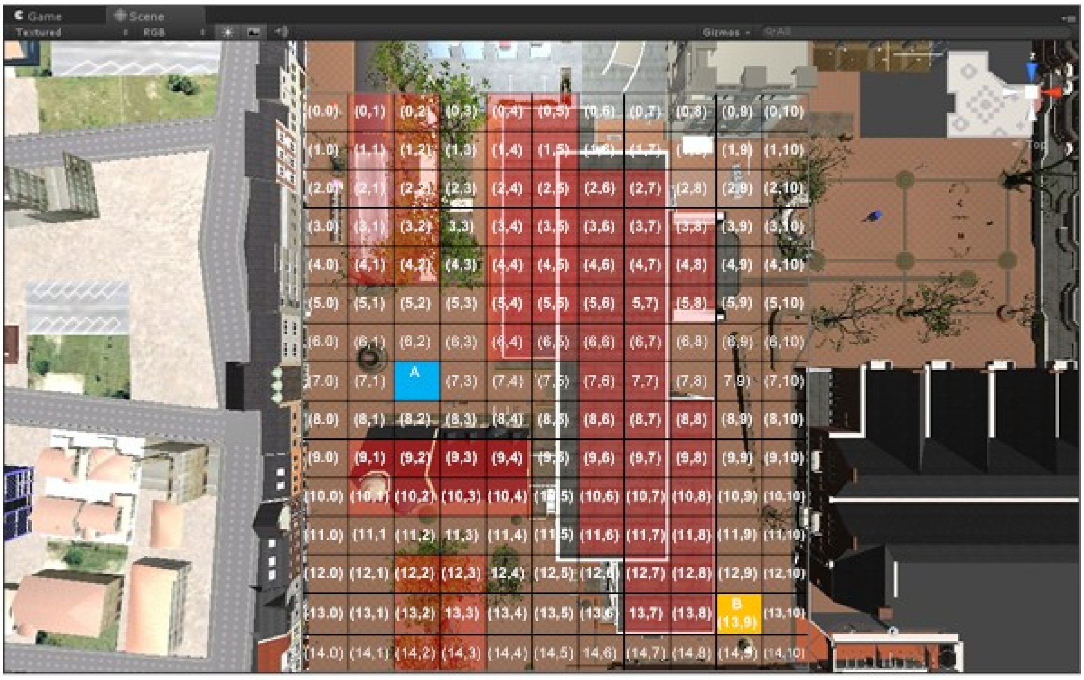


Figure 4.17 Define the world within the grid coordinate (obstacle tiles in red colour area)

Figure 4.18 A* shortest path finding based on the tile movement within grid coordinate

4.1.2.2. 3D space searching for building emergency evacuation

The limits 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 an ever-changing emergency information. Thus, the BIM-VE proposed utilises an adjustable A* algorithm and layered grid graph in response to a building emergency using the AMP system. The adopted workflow with main corresponding classes and methods is expressed in Figure 4.19.

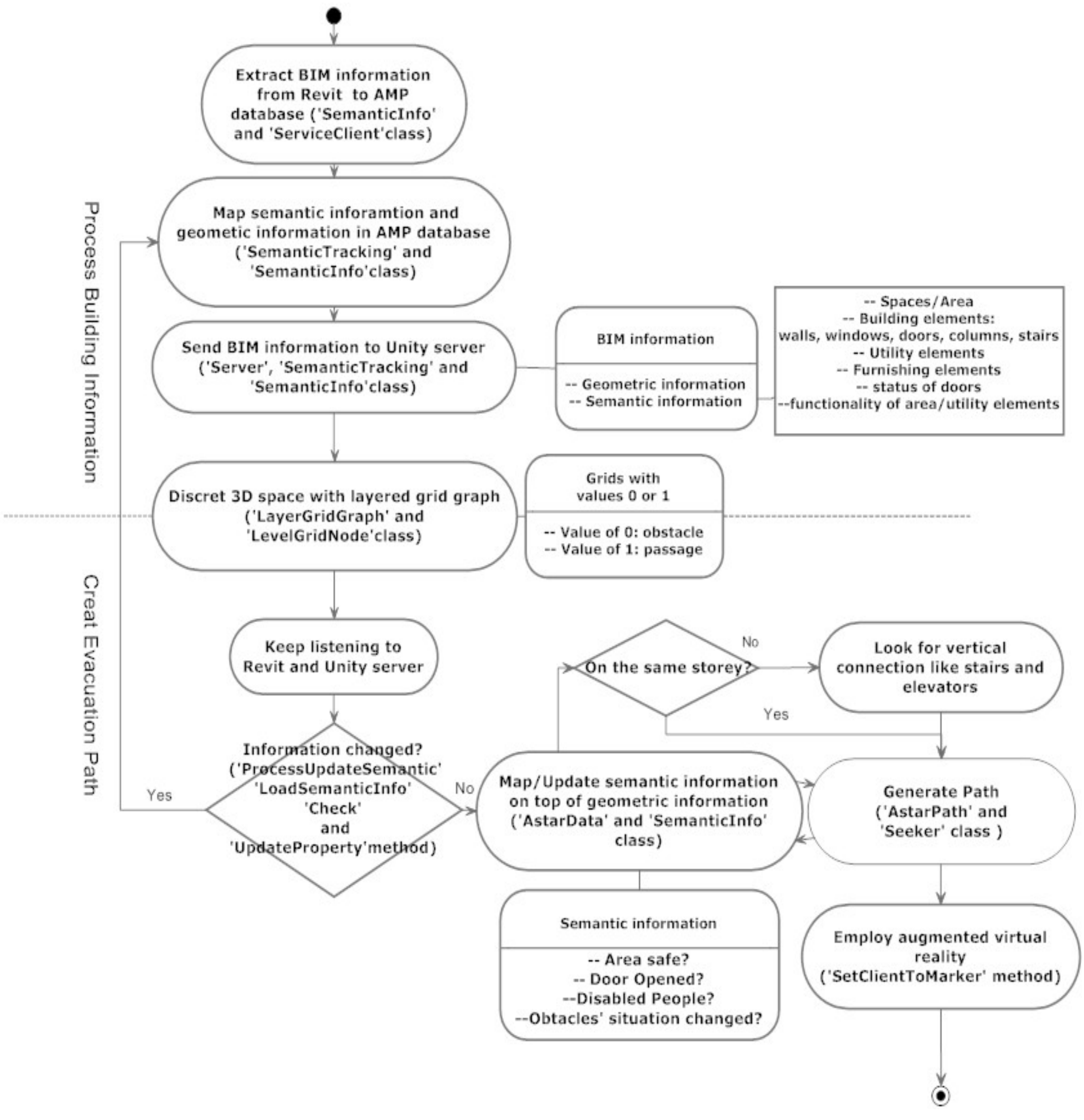


Figure 4.19 The workflow with associated classes and methods for the implementation of the path finding algorithm in the BIM-VE

Process building information

During the stage of processing building information, the data component (i.e. Revit

API and AMP system in Figure 3.2) automates building information transferral between Revit and Unity3D server for building emergency design and evacuation guidance. Specifically, the Revit API implements a process to read the current Revit model and write the information to a 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:

- Object types: floor, wall, door, windows, fire alarm, marker, ceiling, roof, and obstacle etc.
- Properties: unique id, floor number of the object, height, volume, width, door status, position marker id number etc.

The Revit API helps Revit interact with the Unity3D server via AMP system to upload and download data. In order to interact with the AMP system, it needs an http protocol interface that is implemented in the 'HttpClient' variables of the class. Revit API checks and connects the selected IP of AMP system (in the combo box of sever setting form) to upload corresponding building information to different AMP systems for various purposes. The building semantic and geometric information are mapped in AMP system based on IDs of building information, and finally sent to Unity3D server. In our current implementation, only one AMP system can run on a machine at any one time, therefore it always returns the single server running on the same machine.

The server component (i.e. Unity3D server in Figure 3.2) is another most important factor which processes semantic and geometric information for purposes. Notably, it has several pre-defined variables that are critical to the BIM-VE's operation because the third party library defined in the 'FbxPlugin' class 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 server component defines the ratio size of rendering model comparing to the standard size of the imported model; it has to define the centre point of the building following the coordinates in the Unity3D

Server to ensure imported model will lay within the limits of the work area; it also uses HTTP protocol to download and upload data for bi-directional information transferral via AMP system.

Create evacuation path

The server component has several variables to define the structure of the semantic data: the 'objName' variable stores the ID generated by Revit API for the imported object. 'Type' stores the object type which is also extracted directly from Revit such as floor, wall, door etc. The 'pNames' and 'pValues' variables store the arrays of properties extracted from Revit by Revit API such as floor number, height, volume etc. This kind of semantic data is checked at the beginning of initialising server component, which initiates a loop to check each 3D object and ID of building objects to find appropriate semantic information for space searching. The 'AstarData' object stores this appropriate information, with the instance allocated to 'AstarPath.astarData' to allow the A* shortest path library access. 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 on 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 the 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 same floor and adjusts the heuristic to ensure the evacuation route proposed passes through walkable areas using the building semantic information. The flowchart of main classes and methods that creates the evacuation path on a layered grid graph and makes the player follow them for evacuation guidance/training is shown in Appendix B. The workflow of how the layer grid graph generator works with A* shortest path library to create 3D discretised space based on building information within the BIM-VE is shown in Figure 4.20.

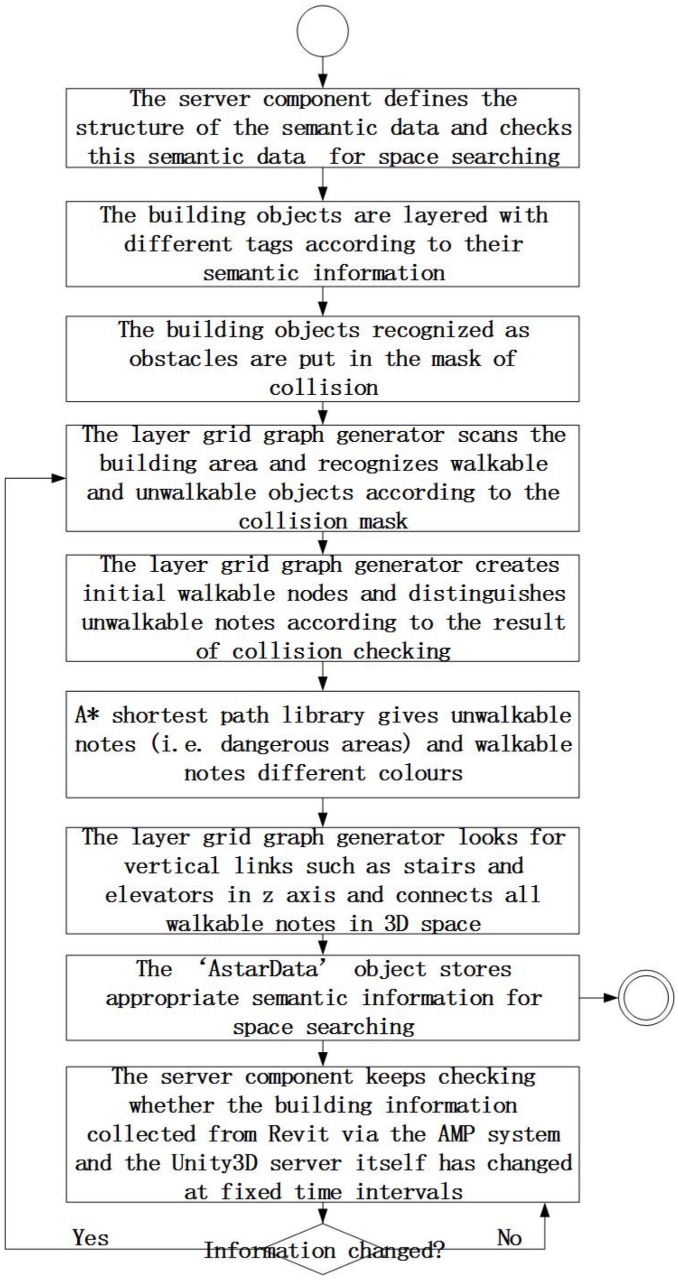


Figure 4.20 Workflow to create preliminary coloured 3D discretised space for shortest evacuation path

The layer grid graph generator (i.e. 'LayerGridGraph' and 'LevelGridNode' class) works with the existing A* shortest path library (i.e. the 'GridGenerator', 'AstarData', 'AstarPath', and 'Seeker' class) to generate layered discretised graph for 3D path finding. It begins with the mapping the building objects and spaces with their semantic information in Unity3D server.

The building objects are layered with different tags such as grounds, walls, doors, and windows etc. according to their semantic information extracted from Revit. The building objects recognised as common obstacles according to their categorised tags like walls are initially put in the mask of collision testing defined by the Unity3D server. The layer grid graph generator scans the building area and recognises walkable (with assigned value 1) and impenetrable (with assigned value 0) objects according to the collision mask. The layer grid graph generator then creates a number of initial walkable nodes on the grid graph and distinguishes impenetrable notes according to the result of collision checking. A* shortest path library gives impenetrable notes (i.e. dangerous areas) and walkable notes different colours.

To accelerate the calculation of note connection, The layer grid graph generator first returns if a note is visible from another on the graph by ray cast (only visible notes are considered). With defined number of node connections (i.e. four or eight), the layer grid graph generator then calculates the grid connections for a single node. It returns if a walkable node is connected to its walkable neighbours in the specified direction. Specially, it looks for vertical links such as stairs and elevators in z axis to get the connections of the grid nodes that are nearest to vertical constructions in different floors. The layer grid graph generator then gets those connections and returns the number of connection. If there is not a connection for a single note, the note becomes impenetrable. If there is a connection for a single note, the layer grid graph generator opens the nodes connected to this node for the implementation of path finding rules in A* shortest path library. After that, it automatically links connected nodes to create preliminary coloured 3D discretised space for shortest evacuation path (Figure 4.21).

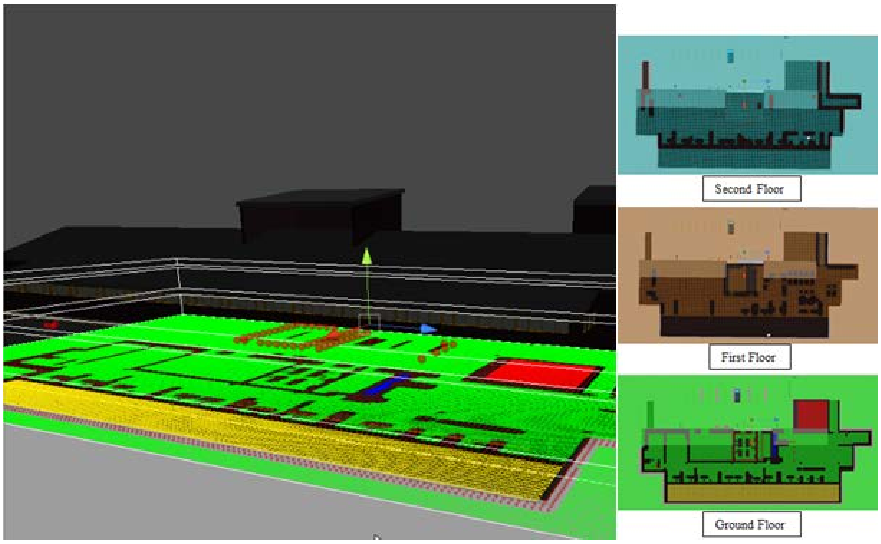


Figure 4.21 Layered grid of nodes and marked obstacles in the multi-floor building (green, brown and blue grid of nodes for walkable area, red nodes for obstacles, yellow grid of nodes for closed spaces)

The server component keeps checking whether the building information collected from Revit via the AMP system and the Unity3D server itself has changed at fixed time intervals because building information changes very fast during the fire emergency, and if necessary changes whether layered building objects belong to collision mask in real time. For example, the fire proof doors in normal situation is layered with tag 'door' that is walkable but will change it to the layer with the 'fire-door' tag belong to collision mask that cannot be passed through in fire emergency situation.

Then, the layer grid graph generator rescans the building area and redefines walkable and impenetrable objects. It then adds all connecting nodes to the stack and sets the area variable (0 for impenetrable and 1 for walkable) to area. The layer grid graph generator creates the index list for nodes and grid graph separately to fulfil 3D space searching of the building with many floors. In addition, the layer grid graph generator is planning to use 'UpdatePenalty' method to update penalty value for the node (i.e. the level of walkability) to create the special grid graph for disabled people, which means some walkable notes that have low level of walkability become impenetrable for disabled people.

The layer grid graph generator destroys this graph when the Unity3D server redefines the objects layers or logs out. During this process, the ‘RemoveGridGraph’ method cleans up the node arrays even are not used. ‘RemoveGridGraphFromStatic’ then clean up a reference in a static variable which otherwise should point to this graph forever and disturb the BIM-VE from creating a new graph.

As for A* shortest path library, 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. On the coloured 3D discretised space, the process to create the evacuation path and make the characters follow are shown in Figure 4.22. Specifically, the ‘seeker’ class is responsible to call the existing A* shortest path library and put the path finding rules on the updated layered 3D discretised space in the Unity3D server and clients through the path finding algorithm interface. The ‘CustomSeeker’ class is the leading derived classes inherit from the ‘Seeker’ class. When ‘CustomSeeker’ class detects whether there are enough walkable nodes to construct the shortest path, it will use the ‘Seeker’ interface to run the A* algorithm and return the result to show the dynamic shortest evacuation path on the layered 3D discretised graph for emergency evacuation guides/trainings. Its object is an agent/virtual character to visually follow the ‘Seeker’ object results (i.e. best evacuation path) to teach end users evacuation skills, with a float value used to adjust its movement speed.

The ‘pathMode’ variable indicates if the current application running is single path (one start and end point) or multiple path (one start and multiple end points). The single path model can guarantee the evacuation path is the shortest one for end-users to save evacuation time. However, the multipath mode can give end users more ways to evacuate out of the building because people (e.g. the disabled) sometimes need the safest evacuation way rather than the shortest evacuation path. The ‘DrawPath’ and ‘DrawMultiPath’ method draw the single coloured shortest (i.e. one start point and end point) and multiple coloured evacuation path (i.e. one start point with multiple end points) according to path mode the end-user choose.

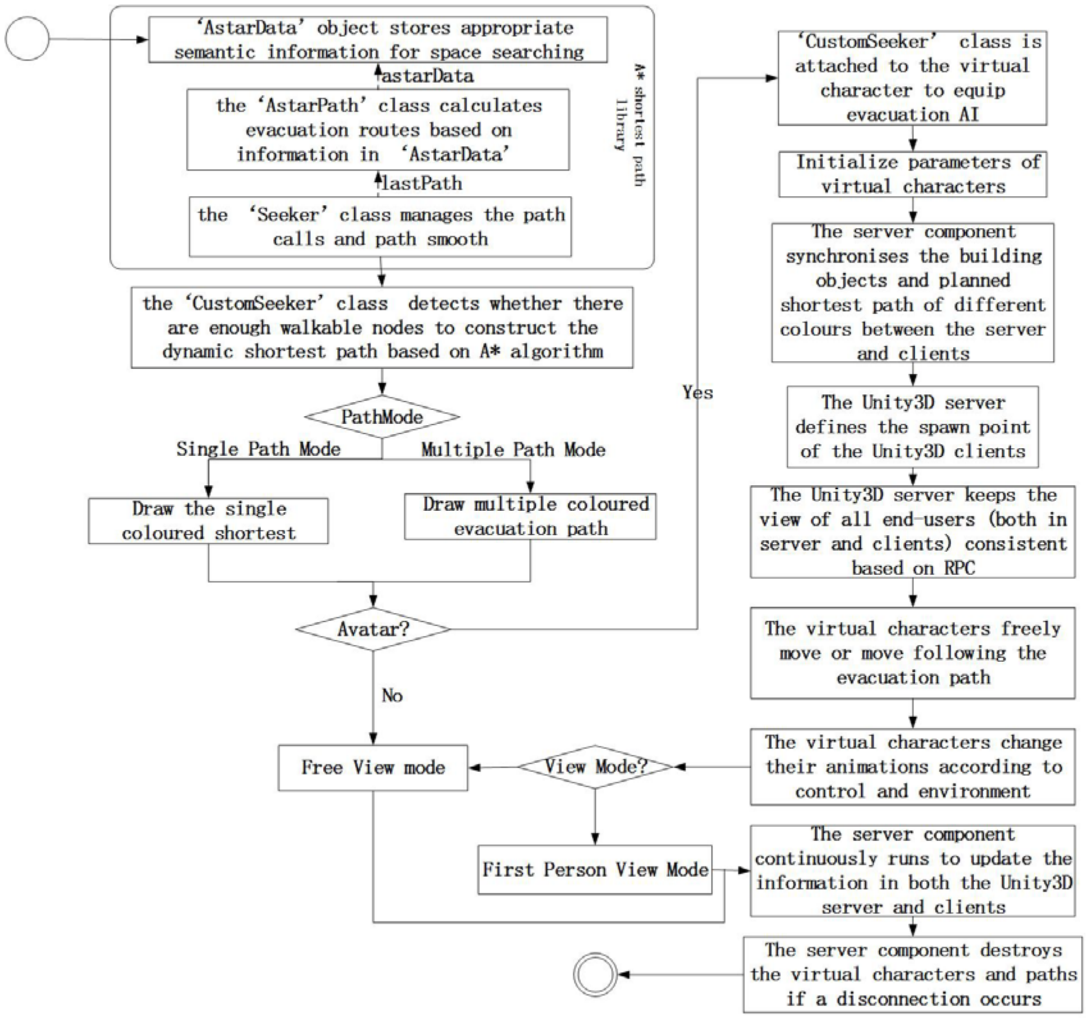


Figure 4.22 The flowchart to create the evacuation path on the 3D discretised space and make the player follow them for evacuation guidance/training

The BIM-VE shows all agents/virtual characters following evacuation paths from different clients together in the unified platform (i.e. the Unity3D server) to monitor evacuation situations. It also synchronises the recommended evacuation path (generated by Unity3D server according to real time building information) with various clients to provide all end-users evacuation guides. Referencing to this evacuation guide, the end users can define their personal evacuation paths in different clients, which can then be synchronised back to Unity 3D server based on RPC. The 'CustomSeeker' class is attached to the virtual character to equip evacuation AI for evacuation training and guidance within the BIM-VE. To update the shortest evacuation path in real time, the server component first need to initialise several parameters, including the ids of the character, path, and client; the options of input and output devices; the predefined seeker component in the space searching library; the components of Unity3D server; the virtual character that is initially shown in the spawn area; the spawn point of virtual characters; the 'clientlist' variable; and the colour of evacuation paths. The server component then generates the IDs of new clients, characters, and paths in different colour if there is a new connected client. It runs several initial functions to synchronise the building objects and planned shortest path of different colours between the server and clients.

The Unity3D server can define the spawn point of the Unity3D clients for the unexpected start of virtual trainings. Based on the IDs of moving characters (i.e. the 'cid' variable), the server component checks client list and brings the position of the available clients to the spawn point defined by the Unity3D server, and keeps the view of all end-users (both in server and clients) consistent based on RPC.

The virtual characters have ability to free move (to finish emergency tasks) or move following the evacuation path (to get evacuation education and guidance). The 'cid' variable stores the ID of the character being controlled by the users to allow Unity3D server to monitor evacuation behaviours. The 'state' variable indicates the current movement status of the player: standing, walking, running etc. to mimic evacuation behaviours within the BIM-VE. According to end users' control, the server component would issue appropriate actions to the virtual characters in different clients to respond the emergency environment based on their IDs (i.e. 'cid' variable). Thus, the Unity3D server can monitor and record evacuation behaviours of all clients in the virtual evacuation experiment or guidance.

There are two view mode options available for the player to switch between; these are free view and first person view. The free view is similar to the view of building design software, which allows end users to holistically carry out building interior design and understand the emergency situation/evacuation skills. The first person view mimics the vision of people and can work with virtual reality technology to immerse end users into virtual environment for virtual evacuation experiments and building emergency design visualisation. The BIM-VE provides the comprehensive graphic user interface to change the view of the virtual character such as first person view and free view of following the shortest path. If end-users choose the first person view, the BIM-VE allows 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 view mode, the virtual character can 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 server component continuously runs to update the information in both the Unity3D server and clients, such as the shortest evacuation paths according to path mode (single or multiple), and the position and animation of virtual characters. If a disconnection occurs, the server component destroys the virtual character with its corresponding evacuation paths and clears its ‘charid’ in the ‘clientlist’ so that the new paths of connected clients can be generated to provide continue and clear emergency guidance/educations within the BIM-VE. For example, the server component stops the moving characters (based on ‘charid’) and to clear their following evacuation path (based on ‘pathid’) to keep 3D space clear if the clients disconnect from the Unity3D server.

4.1.2.3. Augmented virtual reality and mobile evacuation

According to major components of mobile computing (i.e. utilising portable computers and wireless networks to respond to surrounding environment indoors and outdoors based on user location while user is in motion) (Rebolj and Menzel 2004), the BIM-VE can further utilise augmented visualisation technology to mix the virtual and real worlds when the building design is constructed. This allows a 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 recognise the artificial markers to map end-users' positions between the virtual and real. Specifically, the Unity3D clients implement the metaio SDK on mobile devices, which turns on the mobile camera to scan the position marker, helping end users 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, 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 'makerID' is linked with a location that is specified by semantic data in the server component. When an object is detected as a 'markerID' object, the system records the coordinate and the 'markerID' number.

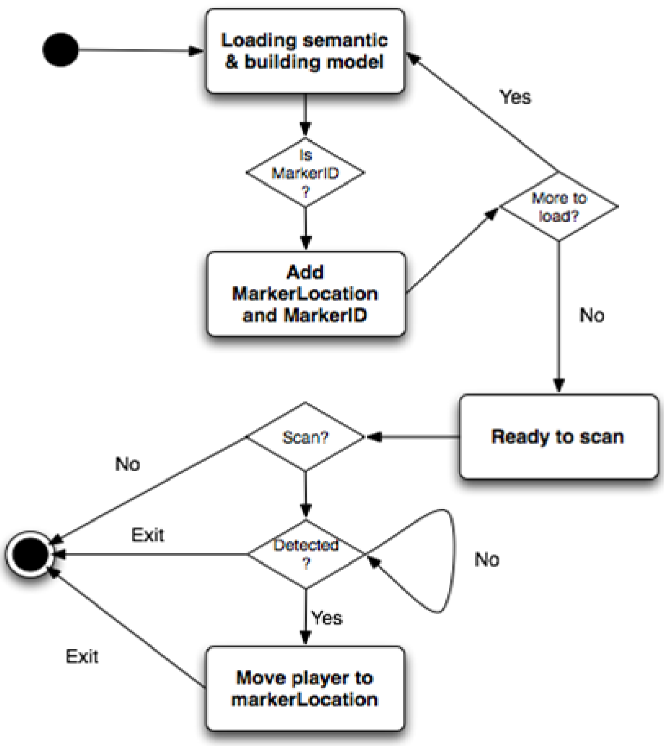


Figure 4.23 Scanning pattern on mobile devices

Figure 4.23 illustrates the work flow used for locating position of the user. On application running, the Unity3D clients load building information from server component based on RPC and initialise the scanning process by reading a configuration file defined in metaio SDK. The clients then construct empty ‘markerLocations’ and ‘markerID’ variables. They continuously runs on each frame firstly checks the camera status (i.e. turn on or turn off), then begin scanning when the camera is turned on. If position markers are recognised, the clients work with metaio SDK to get and move virtual characters to the location of the detected ‘markerID’ objects and turn off the camera.

The coordination of virtual location and real location are defined in Revit and mapped in server component, and finally synchronised with different clients to help end users find their location during the emergency evacuation. When a marker is recognised in the real world, the position of the end-users will be found in the BIM-VE.

In addition, 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 mini map and a 3D model. The mini map gives an overview of the building layout and helps the user keep track of current location. The server component references the player position 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 server component then displays the Unity3D server and clients’ evacuation path on the appropriate position of 2D map. In a building with multiple floors, the mini map shows the current floor map and automatically switches when the player moves to another floor. Currently, the function 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 the 2D image.

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 (recognised by position markers) to the safest point (defined by server, e.g. 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 (i.e. not easy to climb stairs or quickly pass through dangerous areas). By recognising 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.

Specifically, the ‘AddMultiPoint’ method adds all location points of mouse click to a list of end points to allow multiple path evacuation guidance. The ‘SwitchToSingle’ and ‘SwitchToMultiple’ method allow general end users to switch the path finding mode. Single path finding mode allow end users to define one start and end point, showing the optimised dynamical evacuation path in a superfast speed, while multiple path finding mode give the end users with disability a chance to define multiple end-points to find several evacuation paths that might not be shortest but safety and suitable for them at the cost of path generation speed. Unity3D server utilises the ‘DeleteThisClient’ method to erases the single or multiple evacuation paths (based on path mode) of disconnected clients to keep the path guidance more clear and understandable for evacuation education

4.1.3. Immersive and dynamic emergency evacuation training and experiment

The BIM-VE provide immersive and dynamic evacuation training before the emergency and evacuation guidance during the evacuation, which can get general end-users familiar with the building layout and evacuate out of the fired building quickly and safely. Furthermore, the BIM-VE can also be utilised as the experiment tool to accurately explore human behaviour during fire emergency. This section will introduce framework and workflow to achieve the above functions within the BIM-BE (Figure 4.24). The whole classes with variables and the collaboration of methods are expressed in Appendix B.

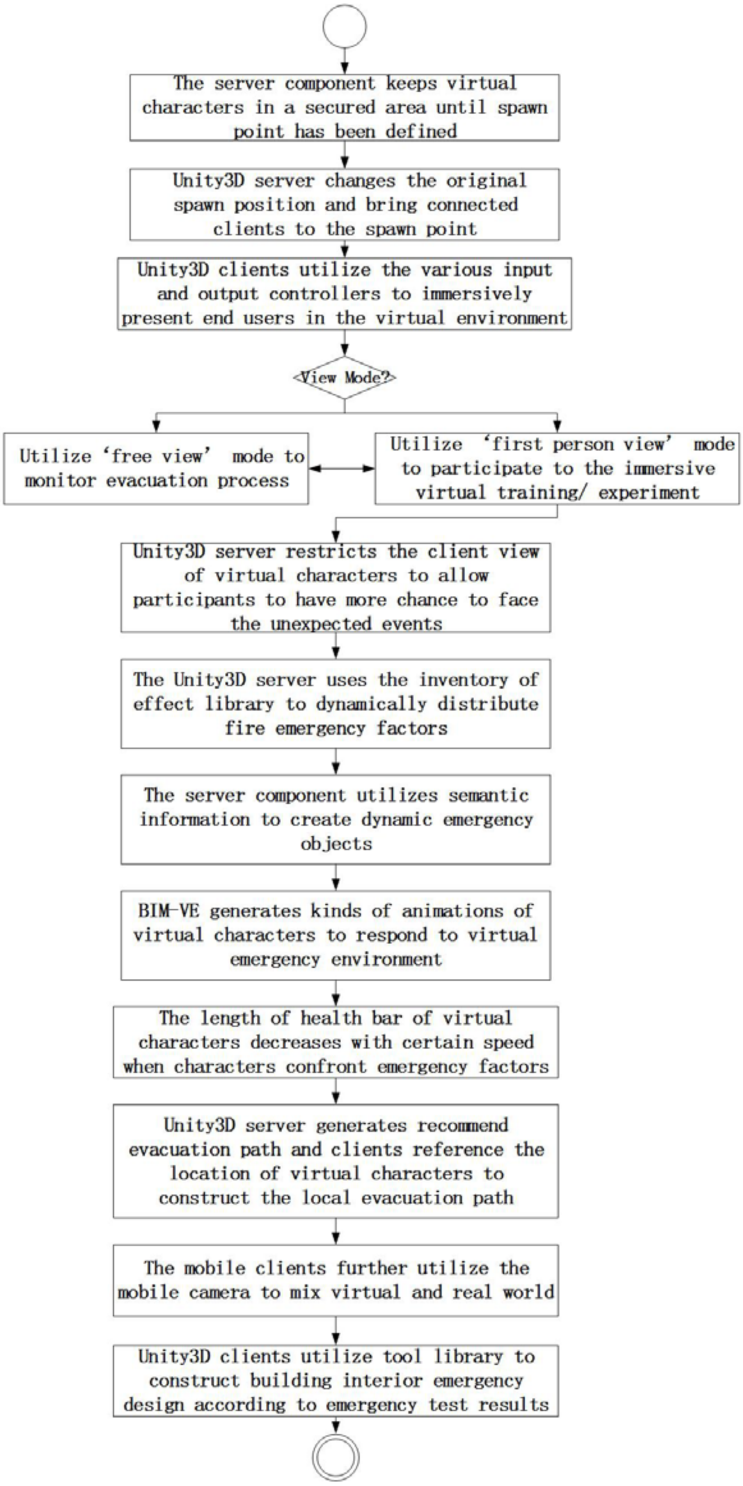


Figure 4.24 workflow to achieve immersive and dynamic emergency evacuation training and experiment

The server component checks whether the secured box function is activated in txt file and keeps virtual characters (i.e. participants) in a secured area if it is before the virtual training/experiment, working with the GUI to show the message "Please wait until server set Spawned Point" if the spawn point has not been defined. The administrator within the Unity3D server can change the original spawn position of the connected clients to prevent the participants in the virtual evacuation training/ experiment from predicting the scenarios, and bring all the participants to the server defined beginning environment within a consistent clients' scenario. Input and output controllers to increase immersive feeling (Figure 3.7) can be free combined through the same txt fire according to requirements of different clients. The end-users in server and clients can choose 'free view' or 'first person view' mode to monitor evacuation process or participate to the immersive virtual training/ experiment. The Unity3D server restricts the client view of virtual character in the first person mode by freezing the rotation of rigid body (i.e. rotation in y axis) and controlling the sensitivity of the view along x or y axis, allowing participants to have more chance to face the unexpected events. The server can release the view restriction of participants after virtual training/experiment according to whether they choose free view mode to review their evacuation records.

The Unity3D server uses the inventory of effect library to dynamically distribute fire emergency factors such as spreading fires, smoke, toxic, activating fire alarms, and setting explosions. All these factors can scale their size, change animations, and influence the surrounding environment according to semantic information stored in server component (that extracts the semantic information from BIM model in Revit via AMP system).The server component is planning to initialise the time of duration of extendable emergency objects such as fire, smoke and toxic, and then to scale and destroy the emergency objects according to their time of duration referenced to their individual materials (the information was extracted from BIM model), which can create dynamic emergency factors to train and investigate participants' emergency behaviour.

The Unity3D server allow the administrator to show a GUI that has a fire emergency effect icon to generate dynamic emergency effects (by clicking effect icons and distributing animations within the BIM-VE) such as fire (the 'OnFireChosen' method), explosion(the 'OnSetExplosion' method), smoke(the 'OnSmokeChosen' method), toxic gas(the 'OnToxicChosen' method) and fire alarms(the

‘OnSetFireAlarm’ method). Then, take explosion effect for example, the ‘SetExplosionBr’ method in ‘Server’ class instantiates the explosion object, working with the ‘SetExplosion’ method to allow the general end users within the Unity3D server to create unexpected explosion events on the mouse-clicked location, and synchronise the explosion event with all connected clients. Similarly, the ‘SetFireBr’, ‘SetSmokeBr’ and ‘SetToxicBr’ methods introduce the fire, smoke, toxic gas objects with the ‘id’ and ‘location’ (influenced by the virtual environment), cooperating with the ‘SetFire’, ‘SetSmoke’ and ‘SetToxic’ methods to define the fire, smoke and toxic gas with certain time-interval on the mouse-clicked location. To reference semantic information to create dynamic emergency scenarios, the ‘OnTriggerStay’ method in ‘SpreadingEffect’ class plans to spread some emergency effects such as fire, smoke and toxic by extending their mesh vertices with certain ratio related to the surrounded wall and floor material obtained from building semantic information. Similarly, based on the properties of building objects (such as walls, doors, or furniture), the ‘Start’ method in ‘EffectProperty’ class initialises their properties related to emergency effect. Then, the ‘Update’ method will generate their destructible effect referenced to their semantic properties.

In terms of fire alarm, the ‘SetFireAlarmBr’ method instantiates the fire alarm object and connect it to the alarm trigger event defined in class ‘AlertTrigger’ in Unity3D server, working with ‘SetFireAlarm’ to synchronise alarm objects and triggered events with connected clients. Specifically, the ‘OnTriggerStay’ method in ‘AlertTrigger’ class defines the dangerous elements (such as fire, smoke, and explosion) that can trigger the fire alarm, working with the ‘TriggerFire’ and ‘Update’ method to activate the light and animation of fire alarm, and close the according fire-proof door (defined in Revit) to dynamically change the evacuation path if the dangerous elements step in the range of detected area. In particular, the ‘ClosingDoorByTriggerBr’ method in ‘Server’ class defines the RPC functions of server-clients framework that control whether the fire-proofed doors can be passes through or not by evacuees based on these doors’ semantic IDs and mesh collider, working with ‘ClosingDoorByTrigger’ to connect fire alarms with fire-proofed doors based on their semantic IDs to make dynamic path finding possible (i.e. triggered alarms close fire proofed doors to change evacuation paths).

During the evacuation, the BIM-VE firstly initialises the parameters related to the kinds of animations in clients. The client plays the 'walking' or 'run' animation when the virtual character is moving and the 'idle' animation when the virtual character is not moving. The client can also play crawl animation when the virtual character is passing through smoke or toxic gas. The administrator in the Unity3D server can produce the virtual fire extinguisher for general end users and allow the participants to fight the virtual fire. Correspondingly, the Unity3D client provides the firefighting animation by pressing 'F' if the end-users pick up the fire extinguisher to test whether the participant has fightfighting behaviour during the evacuation. The server component finally utilises RPC to synchronise these animations between the Unity3D server and clients to make sure different end-users can see each other's different animations to see whether the emergency behaviour is influenced by other people.

The 'OnTriggerStay' method in 'UserVitality' class decreases the length of health bar with certain speed when the virtual character confronts fire emergency factors (with collider tag 'effect') defined in the effect library. The 'Update' method brings the virtual characters back to the spawn points defined in the Unity3D server when the virtual characters controlled by clients lost all their health vitality. This can increase the stress feeling of participants and push them to instinctively respond to emergency environment, which increase the result accuracy of exploring emergency behaviour in the virtual evacuation experiment.

The dynamic emergency effects forces 'cusSeeker' to rescan the area with modified information to dynamically change the evacuation path and finally synchronising the results with the Unity3D connected clients for emergency evacuation training/experiment. Specifically, the server component checks the tag index of building objects (i.e. 'surface', 'wall', 'panel', and 'floor') and references this tag index to put walkable building objects (such as 'floor' and 'surface') to layer 8 and building obstacles (such as 'wall' and 'panel') to layer 9 for further path finding. For those building obstacles in layer 9, it adds mesh collider to them to stop both paths and virtual characters passing through them. It then sets path finding region (defined in ‘AstarPath’ class) to the centre of building and asks ‘cusSeeker’ (defined in ‘CustomSeeker’ class) to update the scan area information to generate recommend evacuation path. The ‘OnServerSetEndPoint’ method in clients automatically sets the original location of virtual character as the start point, accessing to the defined exit end of server to construct the local shortest evacuation path for clients. The ‘SetStartedLocation’ and ‘SetEndedLocation’ method allows end-users in clients to define the start and end points of the evacuation path by mouse clicking on the floor to find recommended evacuation path (generated by Unity3D server) or define clients’ possible evacuation way.

As introduced in Section 4.1.2.3, the mobile clients can turn on the mobile camera to scan the position marker to match virtual position of the end-users within the BIM-VE with the real world. When the construction is on site, the mobile client implements different functional actions required by end-users such as setting start and end point, changing different views of end-users, toggling chat windows, location scanner and minimap etc. to respond dynamic emergency environment defined by effect library of Unity3D server, which allows end users to utilise their smart phone to carry out emergency evacuation training in the real building.

The Unity3D server includes another tool library to provide assistant tools for building interior construction and firefighting equipment locating according to the results of emergency evacuation experiments and training. This tool library can be utilised to build dynamic emergency environment such as collapsing walls and providing firefighting tools during emergency evacuation training/experiment. It can also be used to carry out user engaged building emergency design, which is introduced in Section 4.1.5 and 5.2.2.

The end users in clients can use a GUI to change width, height, angle, colour and texture as the basis of designing the building objects function especially for building emergency design within the BIM-VE. Take wall for example, the ‘AddWallBr’ method in ‘Server’ class working with the ‘WallCancel’ and ‘WallOK’ method provides general end-users a GUI to create and edit walls with ‘BoxCollider’ that cannot be passed through. Then, The ‘EditWall’ method allows end users in Unity3D server to edit these walls such as changing the angle, material, scale etc. for building interior design or emergency situation modification. The methods of ‘OnSliderChange_sliderHeight’, ‘OnSliderChange_sliderRotate’ and ‘OnSliderChange_sliderWidth’ work to allow the end-user to edit dimensions of the wall components such as long, height, angle and width. Similarly, the other building components can be edited by general end users within the BIM-VE.

Overall, the server component defines the approach to allow end users to edit and remove mouse selected objects (including building components like walls etc. and emergency event objects such as fire, smoke, and toxic gas), and generate the updated evacuation path in both servers and clients by rescanning the area for evacuation training/experiment. Finally, the modified building components for the bottlenecks of emergency design can be sent back to Reivt under supervision of the professionals for user-centred emergency design.

In addition, the ‘BeTransparent’ method can set the current shader to a transparent shader, working with the ‘Update’ method to switch the shader between the transparency and original to clearly observe emergency evacuation process and building emergency design.

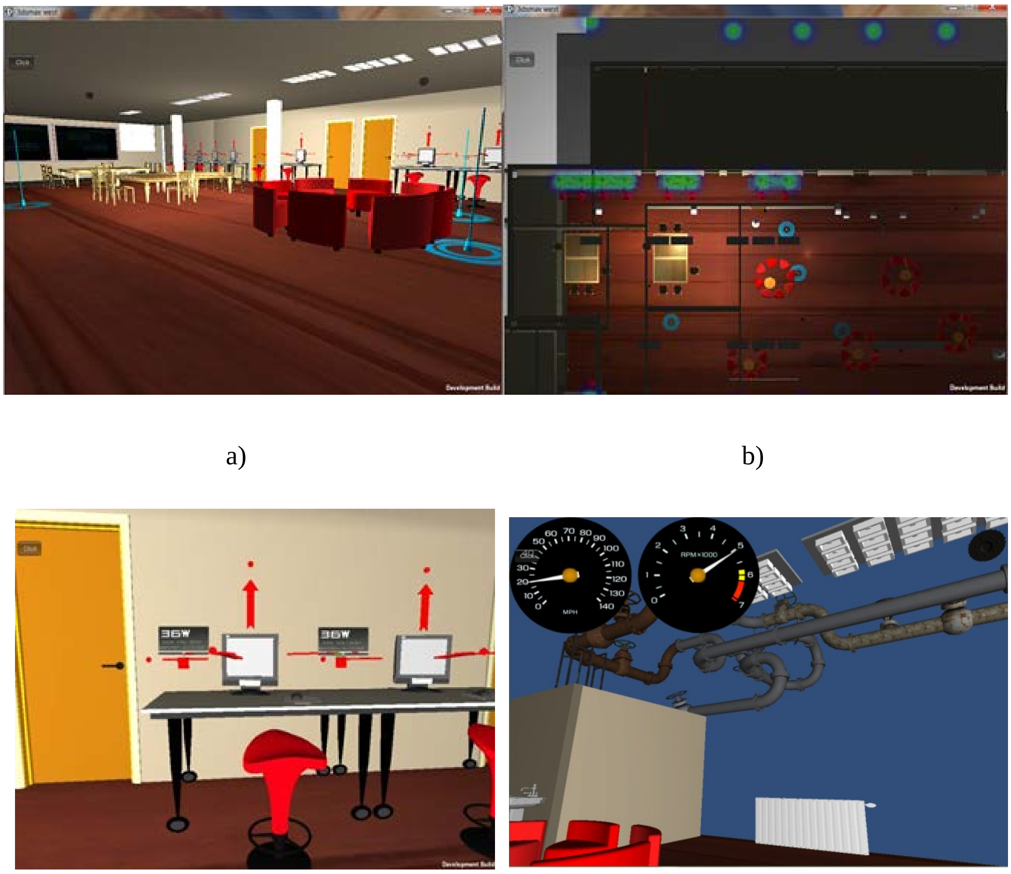
4.1.4. Real-time building information visualisation and monitoring

With appropriate building sensors that collect building information, the BIM-VE can provide a flexible virtual environment that can visualise and monitor building energy usage and emergency situation and keep high degree of space awareness and privacy on top of ontology, which can then add “building performance” dimension to building life cycle. It would also be able to provide adaptable energy saving and emergency management solutions according to ever-changing building information by intelligently utilising BIM and game engine. Although the mentioned function is still under development, the proposed scenarios have already shown its potential benefits to general end users. This section demonstrates the framework and workflow to achieve real-time building energy visualisation and monitoring within the BIM-VE. The whole classes with variables and the collaboration of methods are introduced in Appendix B.

A building management system (BMS) is a computer-based control system installed in instrumented building to utilise a tremendous amount of data to control, monitor, optimise and report the building's mechanical and electrical equipment such as fire systems and security systems for comfort, safety, and efficiency. The BIM-VE is planning to combine BMS to provide comprehensive real-time energy consumption monitoring and emergency evacuation guidance on multiple platforms (PC, Mac, web browser and mobile devices) during the building usage and maintain stage.

Specifically, the BIM-VE further employs two main areas of knowledge engineering (i.e. ontological representation of existing information and semantic building information), GPU, and .NET framework to make building performance visualisation and management possible. Building ontology, sensor ontology and supporting ontology play the key role for agents to collect and understand building environment parameters. With continuous ontology enquiries, the BIM-VE can understand the real time building situation (such as abnormal electricity or fire emergency etc.) and apply the suitable implementations to transfer the necessary building performance information to recognisable data format such as .txt. According to Gershon and Eick, it is easy for observer to understand the building situation if the related building information is represented in the context of familiar physical space because perceptual capability of human being are tuned to the physical world (Gershon and Eick 1995). With the API connected to AMP system, the building information can be automatically transferred and updated in the BIM-VE. The BIM-VE reads and simulates various kinds of building performance data stored in txt file on top of detailed BIM model by .Net framework (Figure 4.43).

Basic classes and functions collaboration for real-time building information visualisation and monitoring is shown in Appendix B.



a) b)

c) d)

Figure 4.25 The simulation to visualise and monitoring building performance in 2D and 3D

The Unity3D clients activate the first person camera (to see 3D real time building information for immersive understanding) and forbid the top down camera (to observer building environment in 2D for holistic understanding) as default. There is a virtual button named ‘Click’ on the top left corner of the screen to change the activated camera by clicking the virtual button. Similarly, a keyboard shortcut (i.e. by typing ‘m’) can fulfil the same function. There are three methods to visualise the captured data: the surface shading, the geometry shape, and interactive graphic user interface (GUI).

In terms of the surface shading, the temperature around key instruments (e.g. computers) in the forum room of Cardiff Engineering School can be taken from the sensors and mapped to provide approximate visualisation of temperature changes across the space (i.e. blue and green mixing area in the Figure 4.25 b)). The mapping colour of the areas would turn red if the temperature is abnormally high, which indicates that there might be an emergency situation there. Specifically, the Unity3D clients utilise the ‘canDraw’ variable to judge whether to plot a heat map image on 2D and 3D map according to the coordination data for heat resource in the text file. The shape and size of heat map image are controlled by the ‘points’ and ‘pointRadius’ variable. With data collected from sensors, the ‘Update’ method combines with ‘ClearPoints’ method to clear the heat map image, working with the ‘lastTime’ variable to update the heat map image every 5 seconds. The ‘OnBecameVisible’ and ‘OnBecameInvisible’ methods allow the end-users to utilise the GUI to show or hide the heap map image.

Another example for surface shading is that whether the key instruments works can be determined by whether the instruments are highlighted in context of the BIM model. And this can help end-users find the faulty devices in the monitoring building. With these two kinds of surface shading, not only the real-time distribution of energy consumption can be illustrated, but also the potential risks that may cause emergency situation can be detected. Take chairs for example, the ‘Start’ method in ‘chari’ class stores the original material colour of chairs in the ‘oldColor’ variable. The ‘Update’ method reads the text file (in the ‘D’ drive) which information collected from sensors, using the ‘sitDown’ variable to judge whether the chairs are occupied or not and then to highlight the occupied chairs.

As for the geometric shape, peg shapes (the blue circle with a pin) visualise occupants’ positions in the building to help find occupancy density in the building and direct the occupants to effectively evacuate during the emergency (Figure 4.25 a)). Specifically, the ‘Update’ method in ‘randomSetPos’ class reads the data of text file collected from position sensors and dynamically changes the coordination of peg shapes to represent human being’s positions within the BIM-VE. Similarly, the arrow shapes can demonstrate air-flow in the space (Figure 4.25 c)), which can then be referenced to judge the direction fire spread with the help of temperature change of the space.

Well-defined interactive GUIs allow the end users to get complex and semantic derived data that cannot be depicted meaningfully within the 3D model. For example, if end users select the power outlet in Figure 4.25 c), the power usage of outlets can be displayed by Arabic numerals with watt unit. Furthermore, how many percentages of power this outlet is using compared to all other outlets within the space can be demonstrated by the horizontal scroll bar. Specifically, the 'Start' method in 'chazuo' class initials the material colour of electricity sockets and slide scroll bar. The 'OnMouseDown' method creates a virtual temporary button (controlled by 'temp_button' variable) and changes the colour of the sockets' material to red (controlled by 'colour' variable) when the end-user uses the mouse to click on the electricity socket. Reference to the number of virtual temperate button, the 'Update' method changes the style of slide scroll bar to clearly demonstrate the electricity consuming percentage of single socket or multiple sockets. If the end-user clicks twice on the same socket, the 'OnMouseDown' method changes the colour of the sockets' material back to the original one (controlled by 'oldColor' variable), then the style of slide scroll bar will also be changed accordingly. The 'Label' variable in the 'lab' class is utilised to define the text of label in the BIM-VE. The 'address' variable in 'address_ary' class directs the paths of readable text files collected from sensors for electricity consuming. The 'Update' method works with 'power' variable to construct equation 'avgPower×avgPower.Length = allPower×power.Length' to show the average electricity consuming percentage of selected items comparing to the total electricity consuming. The 'Update' method in 'ProgressBar01' class judges whether the electricity consuming percentage is higher or lower than average electricity consuming percentage, and uses slide scroll bar to show how many percentage the result is higher or lower than average percentage. The 'Green_red' variable turns the slide scroll bar into red or green (i.e. red colour for the higher percentage and green colour for the lower percentage).

Similar to power outlet, if the end users select the pipe hidden in the walls or celling, the flow speed, the flow direction, and the pressure can be shown in details within the interactive GUIs (Figure 4.25 d)). In particular, the 'Update' method reads the data of text file for water speed and pressure collected from sensors and utilises the speedometer UI to show the results. The end-users can use the keyboard shortcut 'z' and 'x' to show and hide the speedometer UI. The 'curSpeed' and 'curRPM' variables set the original/current water speed and pressure. The 'maxSpeed' and 'maxRPM' variables define the maximum water speed and pressure. The 'speedUp' and 'rpmUp' variables are used to judge whether the water speed and pressure are increasing or decreasing.

With augmented visualisation technology to mix the virtual and real worlds, interactive GUIs can help end-users more effectively understand the building energy and emergency solutions in the real building when the BIM-VE allows the camera of end-users' mobile devices to recognise natural symbols existing in both the virtual and real worlds (Figure 4.26). Finally, the interactive GUIs in smart building system can visually illustrate the building performance related to building energy and emergency situation. And this visualisation, in turn, can assist the fire fighters to distribute firefighting supplies and make corresponding firefighting strategies during a fire.

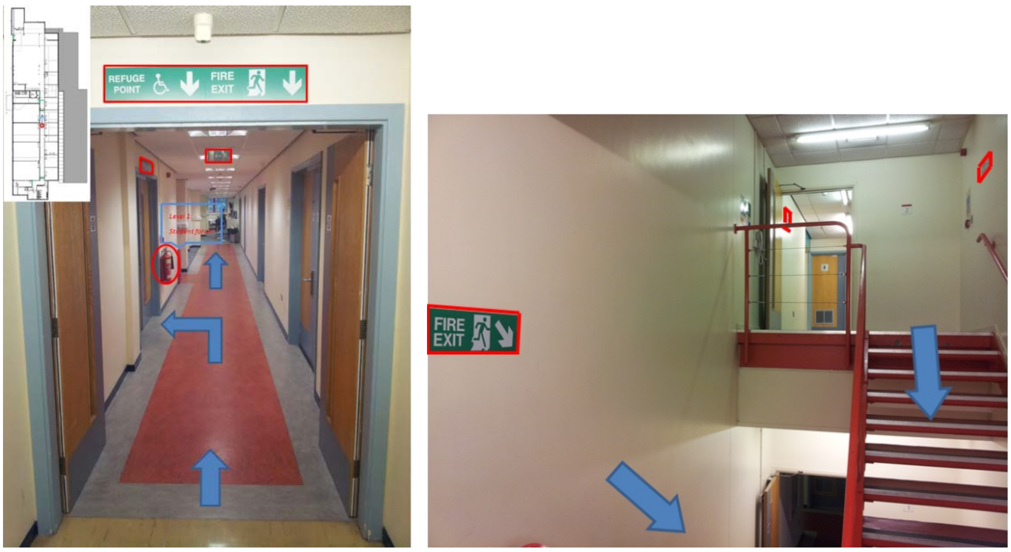


Figure 4.26 The camera of mobile devices to mix virtual and real world to provide evacuation strategies by recognising natural symbols such as evacuation signs

4.1.5. End user engaged building emergency design environment

The general end-users seldom get involved in building design process due to their limitations of professional knowledge. The BIM-VE proposed to build an easy-to-use virtual environment to allow end users to design building interior for emergency evacuation under the supervision of professionals. The BIM-VE provides tools to promote the collaboration between professionals and general end users. Based on their collaboration, this section will introduce the framework and workflow to give end users an authority to manipulate building objects for user-centred building emergency design (Figure 4.27). How main methods in main classes work together to fulfil the potential of user-centred design is expressed in Appendix B.

There are several menu-based scenes which allow clients to connect Unity3D server to carry out user engaged building emergency design in 'Game' scene. These menu scenes have three public variables to control the skin for the GUI components to use, the backdrop for the menu and the title/name of the game to display on the menu. The fourth variable 'isLoading' is private for different clients and determine whether the game is changing scenes between the menu-based scene and the game scene. The 'OnGUI' method is a Unity3D built-in subroutine and is called to create the GUI elements. The starting of each menu scene is initiated in the 'OnGUI' method (e.g. initialising skins, background style, labels to display the title etc.). It then implements the logic of the GUI buttons on each menu. The 'escape' key on the keyboard can be pressed to get back to previous menu.

Specifically, the 'MainMenu' class is a single script attached to the camera object to show the initial menu based scene for the user engaged building design environment (Figure 4.28). If end users are emergency design professionals, they can click 'Start Server' button in the main menu to connect BIM-VE as administrators who have the authority to decide whether to synchronise modified building information about emergency evacuation back to Revit (i.e. professional BIM software). These administrators are then provided a start server menu which is shown in Figure 4.29

(i.e. the 'StartServer' class is attached to the camera object in the 'StartServer' scene, which is similar to the main menu.) to adjust various settings of server-clients framework.

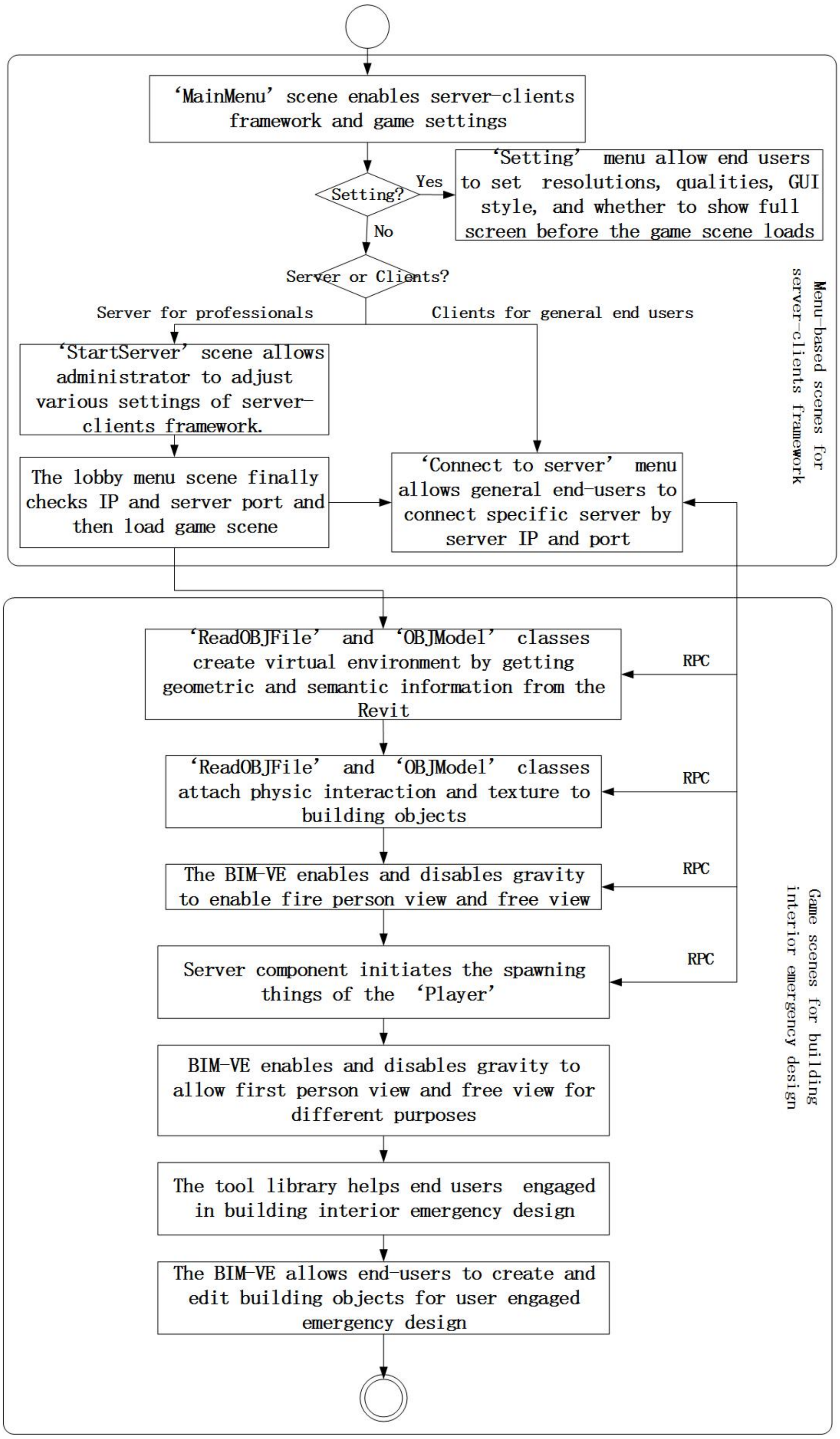


Figure 4.27 The workflow to get end users engaged in emergency design

Figure 4.28 Main menu of BIM-VE for building emergency design

Figure 4.29 Start server menu of BIM-VE for building emergency design

If there is not a connection between a host and clients yet, the start server menu allows the end-users to do some setting via the GUI such as max number of clients and the port of clients, and whether to use NAT or not, which can ensure the specified clients can connect the server. If there is, it will load the lobby menu scene (Figure 4.30) to finally check IP and server port and then load game scene (by clicking ‘Start Game’). The ‘Lobby’ class is attached to the main camera object of the ‘Lobby’ scene. It implements all common menu variables (i.e. backdrop, gameName, and gSkin) and ‘OnGUI’ method. The ‘bolRecievedPlayerNumber’ and ‘intPlayerNumber’ variables allocate each client a unique number. The ‘intPort’ and ‘strIPAddress’ variables allocate the settings that the Unity3D server will use to connect to BIM model via Revit plug-in.

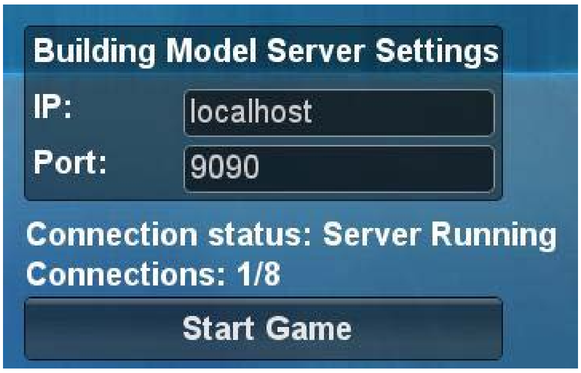


Figure 4.30 Lobby menu of BIM-VE for building emergency design

If end users click 'Connect to server' in main menu scene, they can connect to BIM-VE as clients. These clients are genuine users of a building design (such as occupants and owners) but lack professional skills to get involved in building design process. They are offered a 'connect to server' menu (Figure 4.31) to connect specific server by typing sever IP address and port (controlled by 'connectToIP' and 'connectPort' variable), which can then carry out building emergency design under supervisions of professionals in specific server.

Figure 4.31 Connect to server menu of BIM-VE for building emergency design

If end users click 'Settings' in main menu scene, the 'Setting' menu appears for end users to populate the list menu related to settings about resolutions, qualities, GUI style, and whether to show full screen before the game scene loads (Figure 4.32). The private boolean type variables in 'Settings' class make the menu display different sets of controls and keep track of whether setting have been changed and need updating. The rest of the variables implement two composite controls that consist of a button and list, which displays when a user presses the button associated to each control, which present the list. Then, the 'OnGUI' method implements all of this functionality for the controls. The 'Update' method again looks for the pressing of the 'escape' key to return to previous menu.

Figure 4.32 Setting menu of BIM-VE for building emergency design

The Remote Procedure Call (RPC) is the essential method that synchronises the same function or subroutine between the Unity3D server and all connected Unity3D clients. For example, the RPC subroutine 'GetPlayerNumber' works with another RPC method 'ReturnPlayerNumber' to request a player number of each connected client from the Unity3D server. The RPC function 'LaunchGame' makes server and all connected clients change the scenes to the 'Game' scene.

At the beginning of game scene, the 'ReadOBJFile' and 'OBJModel' classes are attached to the 'BuildingModel' game object to create virtual environment. Specifically, the 'ReadOBJFile' class creates the virtual building environment by getting geometric and semantic information from the Revit plug-in using '.obj' (Wavefront 3D) file. Within the 'ReadOBJFile' class, the 'OBJModel' class creates an array of the individual building objects forming the whole virtual building model. The 'OBJModel' class can be regarded as a container to hold the necessary variables such as the ID number (i.e. the 'intID' and 'ElementID' variable) and name of the building element (i.e. the 'strName' and 'ElementName' variable). Based on these variables, it implements 'get' and 'set' functions (i.e. the 'getElementID', 'setElementID', 'getElementName' and 'setElementName' method). The 'Element' variable holds a reference to the empty prefab, which allows the prefab to contain the correct components such as a Rigidbody to allow for the physics interaction. The 'Materials' variable holds an array of type material in the Unity3D editor, applying various textures to the elements of the building model. The 'aryDoorIDs', 'aryFloorIDs', 'aryRoofIDs', 'aryWallIDs', and 'aryWindowIDs' hold arrays of element IDs, which plays key role in applying the correct texture to five type of elements and creating colliders on the specific elements that cannot be passed through. The private variable 'aryOBJModels' as an array of 'OBJmodel' class holds the data of the elements ready for generating the virtual building environment. The 'aryBuffer' variable acts as temporary storage place to transfer the elements of the '.obj' file from the Unity3D server to clients.

Server component initiates the spawning things of the 'Player' prefabs for end users and stores a reference to each player prefab. By doing so, the spawn script can use this player reference to give each player a unique spawn position because different players aim to design different parts of a building (e.g. their office or home). The 'SpawnPlayer' method instantiates the 'Player' objects of current end-users as a protagonist. The server component destroys various players if a client leaves or if the server disconnects the whole game.

The 'rigRigidBody' variable is used to get the RigidBody component to enable and disable gravity. As default, the BIM-VE provides RigidBody (gravity) to different players to enable fire person view for immersive interior design. Then, the 'OnNetworkInstantiate' method is used to judge whether the main camera has been correctly attached to the 'Player' prefab to enable the subsequent controls of different clients. The end users can show 'in game' menu (Figure 4.33) that is only display after pressing the 'Esc' key during the game with the functionality such as enabling Y axis motion (i.e. free view) and display stats (i.e. individual position and IP address). The 'OnSerializeNetworkView' method is used to send information about the position, IP address and gravity status of a 'Player' prefab to the other clients (players) based RPC for consistent view across the network (i.e. clients and server can see communicate with each other).

Figure 4.33 In game menu of BIM-VE for building emergency design

BIM-VE utilises a tool library (Figure 4.34) to keep the design participants engaged in building emergency design, because this tool library uses ‘click and place’ way to design building interior objects in an immersive 3D virtual environment, which is easy to learn for no professional end users. Specifically, the BIM-VE creates the scroll view components in the tool library because building objects might be too many to show in a fix windows. The objects in this menu are implemented using the public variables ‘Categories’, ‘NumberInCategories’, ‘ItemNames’, ‘ItemPrefabs’ and ‘ItemThumbnails’. Specifically, the ‘Categories’ variable decides the specification of categories. The ‘NumberInCategories’ variable determine the number of items in that category. The details of items (i.e. their names, thumbnail images and references to their prefabs) are then place in the same order. The scroll view is implemented in the ‘OnGUI’ function until an item is selected by clicking the thumbnail of the object within the menu. The ‘SpawnFurniture’ method then creates an instance of the selected prefab in the front of the player. On top of building emergency regulation, the inventory of tool library can help general end users to refine building internal emergency design (Section 5.2.2).

(a)Menu for bathroom (b)Menu for kitchen

Figure 4.34 The inventory library to assist building interior design

To edit building objects, the ‘bolLookingAtObject’ variable is used to judge whether an object is within range and being looked at by the camera of a player when the players get closed to building objects. Then ‘bolObjectSelected’ variable is utilised to judge whether an object within range of camera has been selected to move it around. When the colour of ‘looking at’ circle turns red (i.e. the building object is being looked at and in the range of selecting), players can click left button of mouse to move and rotate the selected object, and finally position it within BIM-VE (Figure 4.35).

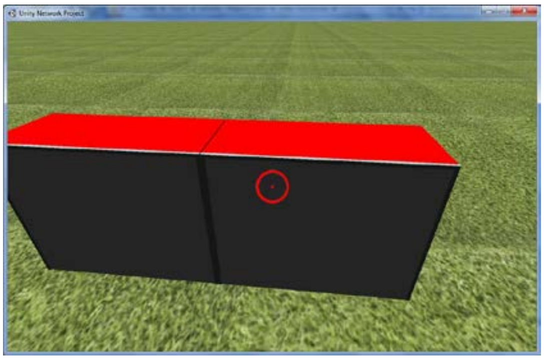


Figure 4.35 Moving and rotating objects

The server-clients framework allows general end-users to help professionals refine building interior design within the BIM-VE (Figure 4.36). RPC functions play the pivotal role in this cooperation between different end users. For example, the RPC 'SetPositions' method allows a player to move the object to its start position on the other players' clients. The RPC 'MoveObject' method allows players of different clients to move this object with them by sending the name of the moved objects and players that are moving them.

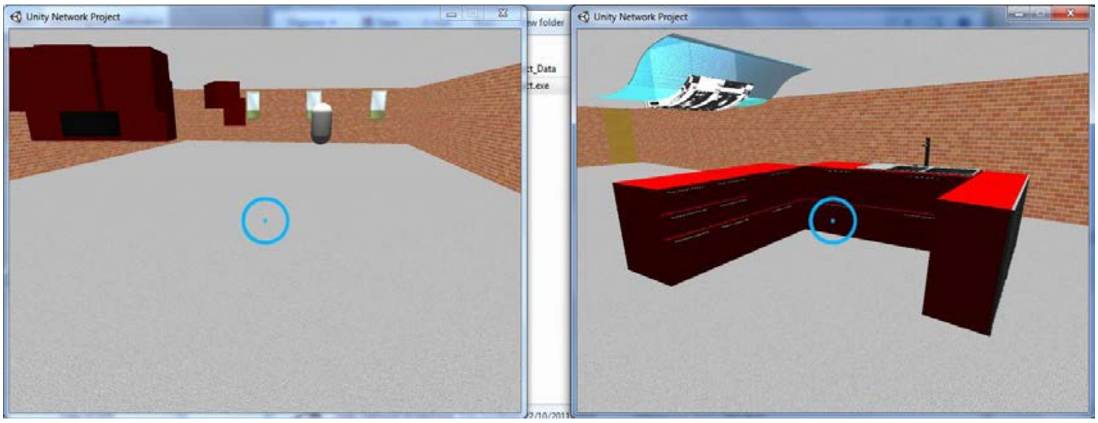


Figure 4.36 Building interior design in clients (right) with server supervision (left)

4.2. Scenario-based fire evacuation modelling

Few methods get general end users involved in a building emergency design process, ignoring whether a building design of professionals will match and affect its intended emergency use. Current computer simulation focuses on prediction of specific human emergency behaviour to overcome this problem. However, a reliable interaction between human, building, and emergency factors responding to actual evacuation is still missing.

Intelligence is provided by humans alone in the real world, but the simulation assigned to computing intelligence also includes non-human entities, such as emergency events. Hence, we can equip emergency events with AI, and assigning them direct control over all the objects (humans, actives, and spaces etc.) of which each emergency event is compromised during the evacuation process. The advantage of BIM-VE is the possible to build a higher level of computing to control the coherence of the simulation of fire evacuation, and to enhance the traditional agent-based system, in which agents with AI behave some local aspects of behaviour, such as events triggering, path finding, and obstacle avoiding.

The BIM-VE provides dynamic virtual experiments to investigate information about occurrences happening during the evacuation process in terms of key factors influencing emergency evacuation, evacuees involved, fire response activities, and spaces where the emergency take places. With AI generator requesting ontological behaviour modelling in Unity3D, emergency events control and coordinate the evacuees' spatial activities according to key factors affecting evacuation, representing their interaction and cooperation.

4.2.1. Key concluded factors for fire emergency evacuation

In the past, the assessment of the use quality of building emergency plan response to evacuation behaviour and well-being highly depends on the insight and experience of designers, who have to reference normative approach and use their own, often biased and incomplete knowledge to foresee how the emergency plan will be used (Perin 1972). In addition, the normative approach has several limitations to building emergency plan. In many cases, the emergency design in use does not work as intended. Some of their features perform better or worse, some differently. Norms are generalisations, in which static and rigid representation of average human behaviour is not enough to suit the uniqueness and context-dependence of human evacuation behaviour and their interaction with building and emergency factors. Although designers cannot fully comprehend how their design will respond to its users' emergency behaviours with limited normative approach, norms and regulation, past experiences and analysis of emergency events, and research results can support emergency design refinement by providing some idea of how human behaves during an emergency.

The evacuation artificial intelligence within the BIM-VE is based on investigation of the fire evacuation behaviour and subsequent fire response ontological modelling. One of method to determine the scope of the ontology is to sketch a list of questions that a knowledge base based on the ontology should be able to answer (Grüninger and Fox 1995). Therefore, it begins with a review of the critical factors (Figure 2.3) and their related questions (Section 4.2.2) that influence fire response performance (Wang et al. 2013). There is no absolutely ‘correct’ way to develop ontologies. Normally, the rough ontology is first proposal, and subsequently is revised and refined by filling in more details.

Human response to a fire emergency includes its perception, interpretation, decision and actions. It is the most important part of performance to predict their fire response before construction because a successful human fire response to the building environment is the essence of successful building emergency design. By literature review, we then built the preliminary fire evacuation modelling/ontology that consists of different evacuation actions and their relationships in four phases of human fire response (i.e. perception of factors, translation of factors and building information, making decision and taking actions) (Figure 4.37). It is proposed to use the BIM based virtual reality environment to create immersive virtual fire experiments with dynamic fire scenarios. This aims to explore human fire response performance without interrupting participants’ focus. The objective of this virtual fire experiments is to validate and extend factors in Figure 2.3, and then consider the research results to enhance fire evacuation modelling in Figure 4.37 to ontology level for evacuation AI (Yuan et al. 2009).

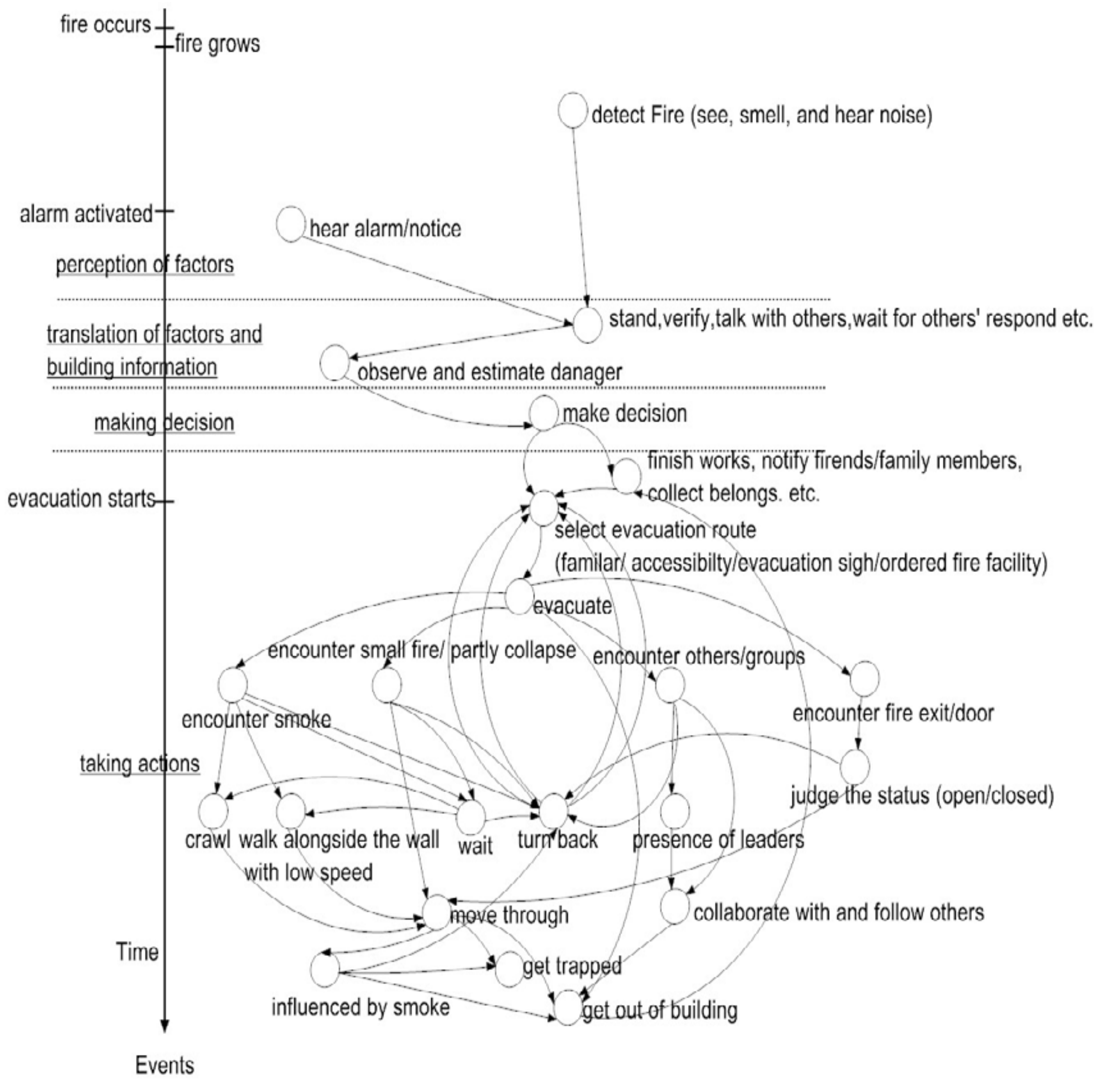


Figure 4.37 Fire evacuation modelling of literature review (Tang and Ren 2012)

Data component utilises library approach to create realistic dynamic virtual experiment. The library approach, where standard components in the library can be archived for reuse to create unexpected events, cannot only eliminate the time waste of repetitive data translation and optimisation of rendering parts, but also add semantic information and animations to enhance the performance of virtual experiments. With data component, the building information can be automatically translated into the virtual environment. However, this kind of translation normally does not include the definition of unexpected fire evens. Administrator then uses library approach to define unexpected fire evens referenced to emergency factors in Figure 2.3.

The Unity clients can utilise virtual reality devices such as the Kinect motion tracker, activate 3D projector system, and Head Mounted Display (HMD) to immerse participants into virtual fire evacuation scenarios to qualitatively enhance the research accuracy of fire evacuation behaviours. Unity clients work in various platforms and connect to the Unity server via Internet, which can easily be accessed by plentiful participants irrespective of their location, which improves the research precision. Thus, combing qualitative with quantificational results, it is adequate to enhance fire evacuation modelling in Figure 4.37 to an ontology level, which enables reuse of domain knowledge from previous researches. In addition, it is possible to integrate several existing ontologies that also described emergency evacuation domain but were investigated by other researchers or come from ontology database (Noy and McGuinness 2000).

This evacuation ontology can then work with evacuation path simulation to build a comprehensive evacuation AI to carry out ontological semantic-based fire evolution simulations to test building emergency plans within a proposed system. If test results are not satisfactory, several iterative steps need to be conducted to enhance the building evacuation design to a satisfactory level. Since the evacuation ontology is specifically designed for a unique building design, the virtual characters with evacuation AI can simulate human evacuation behaviours more accurately to refine the corresponding building design.

Many factors need to be considered in the BIM-VE for accurate simulations, such as fire response performance factors - human nature, fire nature, and building characteristics; building information factors - space/area, building components: walls, windows, doors, columns, and stairs, utility elements, furnishing elements, component material, functionality of area/utility elements etc.; environment information factors- location of people/fire, fire spread orientation, danger levels of area/utility elements, temperature distribution, etc. Since the integration of different key factors could generate a large amount of design alternatives, the usage of knowledge engineering to clearly locate those key factors and to dynamically and intelligently build up a more feasible combination of key factors through pre-defined rules would be essential for the effective fire evacuation simulations for different purposes (LI et al. 2011). With its help, the simulations could be more comprehensive in understanding building information to develop building fire evacuation plans and to provide end-users trusted evacuation guides.

4.2.2. Using questionnaire and virtual scenario to refine the key factors

Since buildings are unique products, the key factors of fire evacuation concluded by literature review are imprecise and uncertain. Indeed, the building emergency design is unlike other design products and cannot be fully understood without knowing how and by whom it will be used. Human spatial evacuation behaviours are difficult to predict and to generalise whilst the building emergency design has to meet the needs of their real users.

The non-deterministic nature increases the complexity of human fire evacuation, which is heavily context-dependent (on such aspects as gender, education, and belief etc.), due to which individual behaves very differently from others given the same emergency event and same built context. A short pre-questionnaire (Appendix C-Experiment Results- Questionnaire) was devised and released to a number of participants before the virtual experiments to investigate the individual information that might influence experiment results. Questions 1-5 simply obtain personal information about the respondents such as name, gender, race, marital status, and age, preparing for unexpected finding from different defined groups. Questions 6-14 are designed to investigate three factor, knowledge, experience and familiarity. Specifically, the knowledge factor includes employment status, professional role, level of education, and study topic, which might influence human fire evacuation behaviours. Experience factors such as experience to play game, to use 3D modelling software, and to use BIM software might also influence fire evacuation behaviour significantly. The familiarity factors focus on how familiar the participants are with the tested building layout and experimental VR devices. Finally, the last two questions consider level of confidence and alertness that are reported to influence fire evacuation time in the real fire. It is hoped that the accumulation of these questions will cover the range of factors that represent a level of need and what may cause the change of fire evacuation behaviours during the virtual evacuation experiment.

To formalise scenarios in virtual experiments, the BIM-VE combines four types of information to produce dynamic virtual experiments: who are the users involved in such emergency (the User), what is the emergency behaviour they perform (the Activities), where physical environment the emergency event occurs (the Area), and how critical factors influence the information interaction.

Observation techniques that are used in the virtual experiments can be generalised into two categories (Glassman and Hadad 2008): direct observation which takes external independent measure of response such as timing, number of times, direct Q&A, event recording or grading via a pre-determined marking scheme; self-report such as post-questionnaires to find the factors that are hardly observed in direct observation. The measurements should provide definition and coverage for factors influencing the human fire response considering independent and depend variables (Bateson and Martin 1986).

Although ergonomics, cognitive science, environmental psychology, and social sciences come from several disciplines of study, all of them can influence fire emergency evacuation (stated in Section 2.2.3). The lack of formalisation of such knowledge in reliable, computationally accessible structures, make it almost unavailable to be utilised by designers. The scenario development will consider integration of these aspects that block the development of fire emergency evacuation.

According to Figure 4.37, the human fire response can be divided into four stages: perception of dangers, translation of danger information, making decisions and taking actions. In perception of danger and translation of danger stage, the questions related to critical factors (i.e. Figure 2.3) need to be explored in the virtual fire drills mainly focus on the observation and judgement of fire dangers. Basically, the factors influencing fire evacuation (Figure 2.3) were simulated and distributed by the administrator in server to see how the participants in clients to respond to these factors. The detailed description of virtual experiment process with three comparable scenarios is described as following:

Perception of dangers, and translation of danger information phases	
Scenario 1 1) Tell the participants that they might communicate with other virtual characters or end-users by GUI if they move closer to them. During their evacuation, emergency environment may kill their virtual characters. 2) The avatars representing participants are placed in one spawn point and tell them to begin evacuation test if they feel their virtual character are in danger. 3) Perceive risks are gradually shown in the following sequence: virtual characters begin to evacuate as a group or individually, fire smoke, toxic, fire, fire alarm and explosion. 4) If they begin to evacuate, record in which stage they begin to evacuate. Go to decision/ action stage. 5) If they did not begin to evacuate, spoken message sound signals warn the participant to evacuate. If they begin to evacuate, record the time from spoken message sound signals alarm sounding to the evacuation behaviour appears. Go to decision/ action stage 6) If they did not begin to evacuate, the 'slow	**Scenario 2** 1) Tell the participants that they might communicate with other virtual characters or end-users by GUI if they move closer to them. During their evacuation, emergency environment may kill their virtual characters. 2) The avatars representing participants are placed in one spawn point, and tell them to begin evacuation test if they feel their virtual character are in danger. 3) Then the 'slow whooping' alarm sounds, but there is not obvious fire perceive (such as evacuation groups, fire and smoke). If they begin to evacuate, record the time to begin to evacuate from 'slow whooping' alarm sounding to the evacuation behaviour appear. And tell them this is false alarm. 4) The 'slow whooping' alarm sounds again. If they begin to evacuate, record the time from the 'slow whooping' alarm sounding to the evacuation behaviour appears. Go to decision/ action stage. 5) If they did not begin to evacuate, perceive risks are gradually shown in the following

whooping' alarm sounds (play in the phone but not too loud), if they begin to evacuate, record the time from the 'slow whooping' alarm sounding to the evacuation behaviour appears. Go to decision/ action stage 7) If they did not evacuate, they will be asked why they don't want to evacuate and suggested to begin to evacuate by the researchers.	sequence: fire alarm with fire, gradual increasing smoke/toxic, virtual characters begin to evacuate as a group or individually, and explosion. If they begin to evacuate, record in which stage they begin to evacuate. Go to decision/ action stage. 6) If they did not begin to evacuate, spoken message sound signals warn the participant to evacuate. If they begin to evacuate, record the time from spoken message sound signals alarm sounding to the evacuation behaviour appears. Go to decision/ action stage. 7) If they did not evacuate, they will be asked why they don't want to evacuate and suggested to begin to evacuate by the researchers.
Scenario 3 1) Tell the participants that they might communicate with other virtual characters or end-users by GUI if they move closer to them. During their evacuation, emergency environment may kill their virtual characters. 2) The avatars representing participants are placed in one spawn point, and tell them to begin evacuation test if they feel their virtual character are in danger. 3) Then the spoken message sound signals, but there is not obvious fire perceive (such as alarms, evacuation groups, fire and smoke). If they begin to evacuate, record the time to begin to evacuate from spoken message sound signals sounding to the evacuation behaviour appear. And tell them this is false alarm. 4) The spoken message sound signals sounds again. If they begin to evacuate, record the time from the spoken message sound signals sounding to the evacuation behaviour appears. Go to decision/ action stage. 5) If they did not begin to evacuate, perceive risks are gradually shown in the following sequence: increasing smoke/toxic, fire alarm with fire, gradual virtual characters begin to evacuate as a group or	

individually, and explosion. If they begin to evacuate, record in which stage they begin to evacuate. Go to decision/ action stage. 6) If they did not begin to evacuate, 'slow whooping' warns the participant to evacuate. If they begin to evacuate, record the time from spoken message sound signals alarm sounding to the evacuation behaviour appears. Go to decision/ action stage. 7) If they did not evacuate, they will be asked why they don't want to evacuate and suggested to begin to evacuate by the researchers.

Table 4.1 Three comparable scenarios during perception of factors and translation of information phases

The video and audio recordings from both computer screen and external camera can provide primary sources for the analysis of virtual experiments, which includes:

- Recordings were taken of whether the participants perceive the dangers and what time this happen before the evacuation; this is judged by direct observation of whether they hesitate to begin evacuation and look around the nearby environment to find the dangers.
- Recordings were taken of whether they estimate the threat of danger and what time this happen by observing whether they look left and right at different dangers.
- Recordings were taken of whether they try to collaborate and communicate with others before the evacuation; because participants were introduced that they can communicate with other character, it can be observed that whether they try to communicate with other virtual characters before the evacuation.
- Recordings were taken of whether they wait for others to respond first; it can be observed that some participants normally stand or walk nearby rather than evacuating if they find the dangers.

After the virtual experiments, the following post-questionnaire will detail and extend these factors, which include:

- What key perception of factors make the evacuation begin (i.e. increasing fire, evacuation characters, slow whooping alarm, alarm lighting, increasing toxic/smoke, spoken message)

- Is ‘slow whooping’ signal rarely recognised, better use spoken message sound signals near exits will speed up escape times?
- Does facing uncertainty about the danger of the situation increase people’s stress and delay evacuation?
- Does confronting complicated fire environment (processing too much in formation) increase the stress of human and delay evacuation?
- Does estimating the threat of danger influence human evacuation behaviour? How?
- Will people wait for others to respond first if they feel there might be a fire in the building？
- Are people who are not sure the danger of the situation or have duties prior to finish their jobs?

the detailed description of virtual experiment phases is described as the following table to test the factors influencing fire evacuation:

Making decision and taking actions phases
Scenario 1 1) Some doors are removed from Revit. During the evacuation, the avatar representing participants walk through the junction of corridor to see how they choose the evacuation way (to test whether the fire exits will only be used if the doors are open; whether they normally evacuate using familiar routes, usually the main exit, which is often the entrance to a building; how fire doors improve fire evacuation). 2) Some of doors have various evacuation groups beside it (i.e. larger exit door with disordered evacuation group beside it and smaller exit door with ordered evacuation group beside it. 3) During the evacuation, if they confront evacuation group, it is the research point to see whether they want to communicate with them or to see whether they follow their steps and decrease the evacuation panic. 4) Some evacuation groups are allocated to one floor stair, but keep another floor

stair empty; to see how much time it costs from one reference point to another comparing point. 5) Add fires with comparing sizes in some place, it is the research point to test their reacts to the level of fire. Keep adding emergency effects such as explosion. When the avatar faces these effects, it is the research point to test their behaviours such as moving through or turning back or wait. 6) Smoke and toxic gas is similar to fire. (And to test walking speed in thick smoke is slower than normal).
Scenario 2 Similar to previous, but 1) The participant will be placed to another start point. 2) The size and location of fire, smoke, toxic will be changed.
Scenario 3 Similar to previous, but 1) The participant will be placed to another start point. 2) The size and location of fire, smoke, toxic will be changed.

Table 4.2 The scenario during making decision and taking actions phases

Similar to the video and audio recordings of the perception and translation period, many factors need to be observed and investigated, which is divided into three parts: the influence of human factors, building layout, and emergency dangers.

More specifically, the human factors include communication and group preferring, presence of leader, human familiarity and affinity, and human density.

- Recordings were taken of whether the participants try to collaborate and communicate with others after the evacuation; it can be observed that whether they try to communicate with other virtual characters during the evacuation.
- Recordings were taken of whether the participants try to adopt the role of a follower; when the avatar controlled by participants encountered other evacuation virtual evacuees, it can be recorded how many times they try to follow other virtual

evacuees, with the aims of calculating the percentage of ‘followers’ for virtual characters during the virtual evacuation.

- Recordings were taken of whether the presence of leader poses positive affect on the evacuation; it is based on how long and how easy the participants follow the evacuation leader to the safety exits.
- Recordings were taken of whether the participants evacuate using familiar routes based on their person information and performance; it can be noticed that if the participants repeat the same evacuation routes, then the investigation of affinity between the participants and this evacuation route will be carried out.
- Recordings were taken of how the evacuee density influencing the evacuation effectiveness; the performance of avatar controlled by participants within high evacuee density were observed to prove that if higher density means higher probability of fatalities

The building layout describes the accessibility of fire exits, the open fire exits (space), and the dimensions of fire exits.

- Recordings were taken of whether the participants choose the evacuation route with easy accessibility; the conjunction of different routes with different exits is the observed point to analyse; whether they care about accessibility of fire exit because different routes have various level of dangers and obstacles.
- Recordings were taken of whether the open fire exits (spaces) were easily chosen as the evacuation routes; when avatar had to choose the evacuation route. It was a research point to find their open exit (space) preference.
- Recordings were taken to determine the effective evacuation nearby the exit (the width of exits or the ordered passing through); that can be observed if the avatar moved quicker through the exits with ordered evacuation queue.

The influence of emergency danger focuses on how fire dangers change human evacuation behaviours.

- Recordings were taken of what actions the avatar took when facing fire dangerous such as smoke, toxicity gas and fire. The number of different actions (i.e. moving through, turning back/left/right, and waiting) were counted for percentage of their appearing during the evacuation. Specifically, when the participants faced smoke and fire, which can be observed when the avatar ran alongside the walls and the running speed is slower in low visibility.

As the dynamic virtual environment generated by the BIM-VE cannot sufficiently explore all factors influencing human fire response, the post-questionnaire were then utilised to valid and extend these factors, which can be demonstrated in the following aspects:

Collaboration & Group preferring

- Did the participant wait for the response of other people in the virtual experiments?
- Are the participants more inclined to collaborate and communicate with other evacuees during the evacuation?
- What is the participants' preferred role when you begin to the group evacuation?

Social bond

- If the participants recognise their family members or friends during the evacuation, will they try to respond to fire with them as a group as long as possible?

Commitment to prior activities

- Are the people who are not sure the danger of the situation or have duties prior to finish their jobs?

Physical and role position

- If the participants are standing or walking, are they more likely to leave the room to begin evacuation than if you are present in a prone or sitting position?
- If the participants are a follower, are they less likely to panic during the evacuation?
- Does presence of evacuation leader pose a positive or negative affect on their evacuation?

Building Evacuation Team

- If the leader is well- trained for emergency response, do the participants think they can improve the speed of escape and the use of emergency exits? Why?

Familiarity

- Are they prefer to navigate/evacuate to the emergency exits using the main exit of the building (e.g. the main entrance to the building)?
- Which factors would mostly influence their choice of navigation/evacuation route? (i.e. familiarity, accessibility, guide sign, and ordered facilities)

Easy of way finding

- Which position of escape route sign/position marker can easy be noticed by participants?
- What suggestions can the participants give to improve the mobile navigation/evacuation support?

Fire compartments and size

- How automatic closed fire doors improve fire evacuation?

Smoke, toxic gas and fire

- When the participants faced smoke or toxic gas, did they have a trend to crawl through the smoke?
- In the reduction of sight, did they try to walk along side walls to get evacuation direction?

Fire size and growth rate

Did the fire size and growth influence the participants' evacuation direction? How?Different scenarios were applied to different building area with dynamic building layout controlled by server to enhance reliability of experiment results. Our team is currently using the same approach to other education department on design or construction stage. All the results from questionnaire and virtual experiment recordings will be detailed in Section 6.2. However, due to the limitation of time and the BIM-VE system, there are still some questions have not been fully investigated, which provides the future direction to develop the BIM-VE to refine factors influencing the human fire evacuation. These questions can be concluded as:

Mobility

- How do disabled people choose their evacuation path? (high, temporarily reduced, permanently reduced)

The level of fire safety engineering on fire safety

- Are people inclined to choose the evacuation route where the fire safety facilities are in good order?

Building Materials

- How does flammable material for furniture and constructions influence fire evacuation?

Fire compartments and size

- How do fireproof doors prevent fire spread and improve fire evacuation?

Installations

- A "false alarm interpretation" and "only a low amount of perceived risk," which leads to the performance of certain longer-delay activities?

In our evacuation modelling approach, scenarios are assembly of events that represent how evacuees interact with the virtual emergency environment to reach their objectives defined by their specific characteristics and tasks. Events in emergency evacuation describe the impacts and interactions between entities (i.e. building, humans and emergency factors). Entities are structured and connected to each other in order to represent what happens to evacuees in a fired building. It is not a direct prediction of how the individual will behave during the emergency in the building, but rather experiment-based knowledge model for such prediction. Through the recording analysis of virtual experiments (the results are detailed in Chapter 6), the preliminary evacuation modelling of literature review can be validated and extended to the ontological level by this kind of knowledge for the appropriate simulation within the BIM-VE (i.e. Section 4.2.3 and 4.2.4). Thus, scenario-based evacuation model does not have to be considered as an alternative to existing evacuation model, but as a possible augmentation of them. The traditional agent-centred simulations can utilised this scenario-based evacuation model to develop the ontology-driven system, to provide reliable and complete data about building in use for the virtual environments. The balance between agent and simulation depends on the purpose of the simulation and the necessary autonomy degree of characters involved.

4.2.3. Human behaviour modelling

Based on the above-mentioned dynamic fire experiments, human behaviours and capabilities during fire evacuations would be obtained and analysed for specific buildings and then the evacuation behaviour modelling/ontology should be modified considering these results. The BIM-VE can provide the repeatable virtual experiments for iterative process of ontology development. In theory, the results from virtual experiments should validate and supplement the existing literature-based human behaviour modelling to ontological level by utilising ontological reasoning. It should be noticed these results cannot be simply integrated with existing modelling, because they includes heterogeneous and independent domain of data. Ontology can provide entities to interpret combined Who, What, Where and How in a meaningful manner, which make explicit domain assumptions. Unlike hard-coding assumption about the world in programming-language, it is possible to change these assumptions easily if our knowledge about the domain changes. Design decisions in programme are based on the operational properties of a class whereas an ontology makes these decisions based on the structural property of a class. Better still, this ontology can be supplemented with other exiting emergency human behaviour ontologies by analysing domain knowledge.

Normally developing an ontology of a domain aims to define a set of data and structure for programmes to use. In this case, the ontology is a formal representation of human nature, building characters, and the nature of environment as a set of concepts within the fire evacuation domain and their relationships. It is used to reason about the entities within the fire evacuation domain, and can be used to describe it. The ontology includes structures that allow manipulating domain knowledge in a more efficient way; it is useful to the human understanding and validation mechanisms operating on a virtual character for evacuation artificially intelligence.

The simulation-based approaches in other disciplines related to building design (such as structural and energy engineering) have promoted development of new methods to predict human evacuation behaviours in building emergency environment. Simulation techniques have the broad potential when applied to representation of complex systems (Kalay 2004). However, their applications to human-building-environment interaction have been limited to representation of common well-defined aspects of human behaviours. The pure agent-based modelling also failed to represent cooperation and collaboration among agents (O'Sullivan and Haklay 2000) because each agent need to process the impact of its actions on other agents, read their reaction, and re-process its own actions in real time, which would be an extremely hard task for agent based system.

The ontology-based simulation allows for creation of specific instances with property specific values, defining discrete objects and their relationships, which can reduce complexity of evacuation behaviour into manageable structure that might lead less individuality and less arbitrariness of single behaviour. However, it is acceptable this limitation of ontology-based simulation for a fire evacuation scenario. In the sense that rather than looking for a complicated representation of real evacuation, the BIM-VE aims to predict the mutual influence between an emergency design solution of a building environment, and specific, well-defined emergency scenarios.

Although there are several projects working on building ontologies for fire emergency management (Mion et al. 2008; Upadhyay et al. 2009), the methodology used here would be able to integrate BIM, virtual reality, and human evacuation behaviours to produce a comprehensive but unique evacuation ontology for a building design involving less time and financial resources. The evacuation ontology is specially explored and designed for the corresponding building design, which can enhance the accuracy of the evacuation simulation to test the emergency plan of the building design. It is recommended that every building design should have a matched evacuation ontology designed by the proposed virtual building system, which can add the “fire evacuation” dimension to the building conceptual design. Virtual characters can be regarded as the agents that can receive relevant input from the ontology service to intelligently control the interaction between BIM, Game Engine, and environment information to provide the fire evacuation simulation in the tested building design. The evacuation ontologies will include relevant domain keywords, the interrelationship between those keywords, and well-defined rules/goals to capture the agents’ message content to carry out fire evacuation simulation. With this evacuation ontology, the BIM-VE can simulate user’s evacuation behaviour in fire emergency, based on clear representation of evacuation processes from experiments, rather than on autonomous, sometimes arbitrary behaviour of traditional agents generated by their fixed specific set of rules.

The BIM-VE aims to develop a computational simulation approach that is able to represent the accurate emergency evacuation behaviours associated with specific, ad hoc design solutions. There are two steps to organise the evacuation ontology that drive accurate evacuation simulation (Figure 4.38). The first step is to employ the external ontology editor such as protégé to integrate human evacuation behaviours in virtual experiment with validated human evacuation modelling. There are amounts of plugins to support Unity3D. The second step is to use the API of AI plugins such as Playmakers, Uscript, and Antares Universe to query the ontology of evacuation behaviours to directly provide advanced evacuation AI to characters/agents in the virtual reality environment. The evacuation ontology directs consequence of single users’ behaviour, guided by their personal characteristics and objectives, composed by a complex system of decision/action process in a continuous process of affecting or being affected by the emergency environment and by other user’s behaviour. With a querying API in virtual reality environment, virtual characters/agents can makes a large number of decisions and performs conscious and unconscious actions relating not only to the purpose of their behaviour but also context at the same time. Other words, their spatial emergency behaviour comprise not only single evacuee’s actions, but also cooperation and influence between people, building and emergency factors.

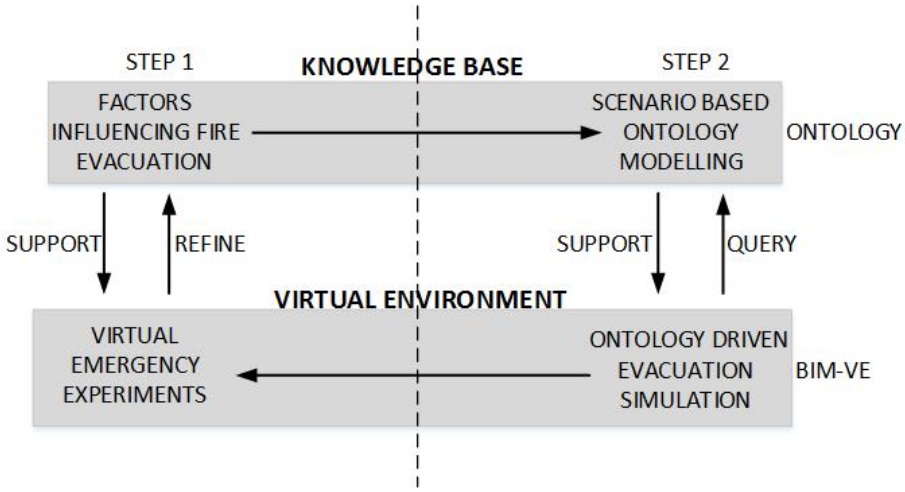


Figure 4.38 Two steps to organise the evacuation ontology and enable evacuation simulation

The virtual characters/agents with evacuation AI can be regarded as an instantiated prefab and distributed into BIM model in order to test and refine the fire emergency plan of a building design. In particular, the instantiated characters/agents utilising skeletal animation such as idle, walking, talking, running, and crawling are manually distributed in a building design according to the real human capacity of a building. The API connected to AMP system automatically keeps both geometric and semantic information from BIM model updated. Finally, the movements of characters associated with optimised evacuation ontology interact with updated building information to carry out the precise evacuation simulation for corresponding building emergency design (Figure 4.39). Several iterative steps need to be conducted to identify the design problems and improve the building emergency plan until evacuation performance reaches a satisfactory level based on existing fire engineering standards (Figure 4.40).

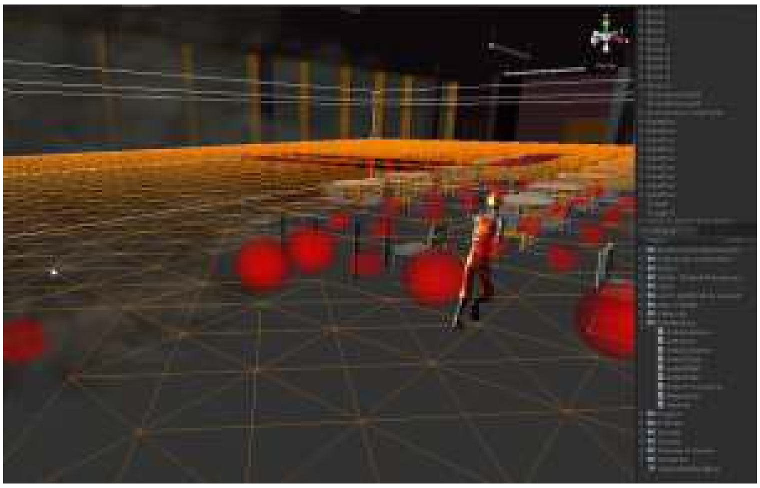


Figure 4.39 Fire evacuation behaviour simulation in the building design

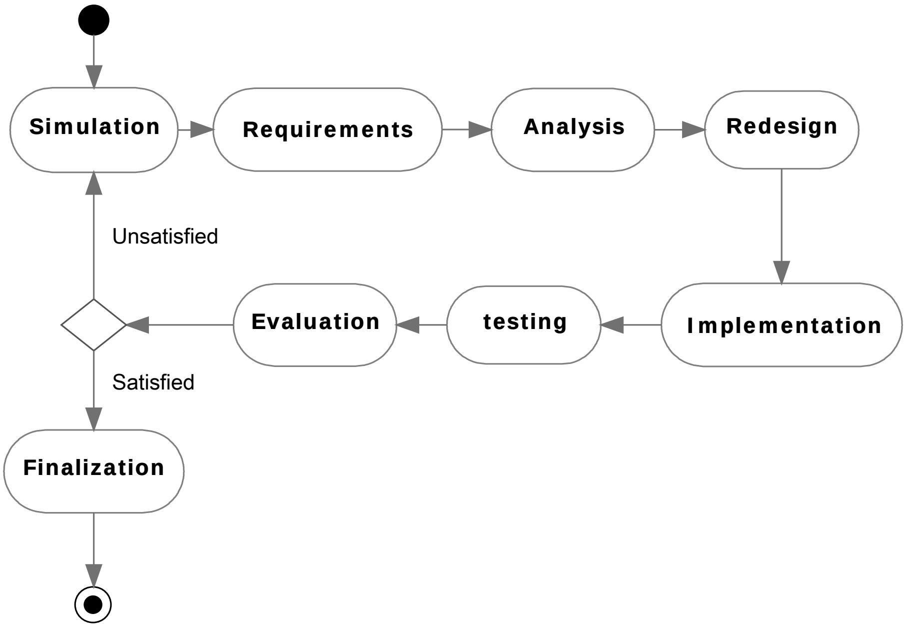


Figure 4.40 The interactive steps to refine building designs by the evacuation behaviour simulation

4.2.4. Scenario based ontology modelling for fire evacuation

A system state-generator play key role in a successful simulation model, which is consists of two prime components (Burdick and Naylor 1966):

- A static component represents the state of the system, including all the entities (e.g. objects, actors, spaces and their variables) in the system, and their relationships;
- A dynamic component represents changes (how the system moves from one

state to another), which is where the system is activated (i.e. where the simulation algorithms are run, generating changes in the states of the objects).

The goal to develop ontology driven evacuation simulation is to share common understanding of the structure of information among people and software agent, and to represent cooperation and collaboration among agents, which would ease the burden of agent based system. The results from both virtual experiments and post-questionnaires are analysed and organised in the form of model. There are several requirements which proposed knowledge model should work with two way information channel to meet within the BIM-VE:

- Representation of all the main factors that influence users' (as evacuees) various fire evacuation behaviours in different building area, including human factors, building factors and emergency factors;
- Representation of the interaction between humans (as evacuees), buildings and emergency environment in different stages of fire evacuation and how they are affected by each other. Therefore, a context-dependent and scenario based model is demanded. All the activities performed by user throughout the fire evacuation process in the experiment should be presented in this model.

According to such structure, the BIM-VE consists two parts: a knowledge model (built by ontology) to afford hypotheses about reaction to emergency scenario and built environment, and a dynamic virtual environment (via two way information channel) to actually simulate fire evacuation. The virtual environment represents data and concepts about the system of entities comprising the building (building components, spaces, furniture, equipment etc.) and emergency environment (fire, smoke, toxic gas etc.); the people who will interact with them (occupants, visitors, workers etc.) and the process of evacuation (events and scenarios) will be characterised in knowledge base.

With the rapid development of Semantic Web technology, ontology has become central part of many researches as knowledge base or model. The choice of the ontology model gives us the possibility of representing all the different heterogonous entity classes in a homogeneous form, and make clear all the related semantic and relations. Specifically, it provides a formal conceptualisation structure to describe and model a domain of knowledge. A typical ontology is composed of classes, instances of class, properties of class and relationship between classes. As one of its advantages that is not just readable by human but computable by computer, ontology offers great flexibility to let researchers understand how human behave in fire situation and more importantly to support computer application such as game engine to simulate human behaviour. Therefore, the BIM-VE can utilise ontology as a knowledge model to work with geometric and semantic building information to represent interaction between human, building and emergency during an evacuation process within a virtual environment.

The ontology-based system allows for creation of specific instances with property to define discrete objects and connect them in the simulation level. To develop this knowledge model and signify their semantics, we select ontology editor Protégé 3.5, a java based open source tool as ontology development environment. There are many methodologies available to develop an ontology. In this study, we choose to use Ontology 101 Guide since it is suitable for development from scratch or from existing semantic resource, which many studies in other areas have implemented. In addition, OWL DL (i.e. Web Ontology Language Description Logics) has been chosen as ontology language due to its expressiveness and reasoning capability.

To develop simulation environment where the virtual evacuation is computed, simulated, and visualised, the Game Engine Unity 3D that consists the 3D graphics simulator and AI editor is chosen. The 3D graphics simulator defines the place where the entities (people, building, physical objects and emergency objects) are graphically represented in a 3D space, and where evacuees can observe the objects' dynamics (other people's behaviours, fire emergency's spread, building performance during a fire etc.) while the simulation is running. AI editor plays key role in where the human emergency behaviours' data and scripts support the necessary simulations within the BIM-VE. These two components can work together to change and update the evacuation simulation in real time. For example, if an evacuee moves through a corridor with fire emergency, his spatial coordinates and speed property will vary according to the judgement of danger level.

According to Section 4.2.1, comprehensive list of concepts during the fire evacuation without worrying about overlap have be expressed. The next step is to combine virtual experiment results to develop the hierarchy and properties of concepts following the combination development process in Ontology 101 Guide. The ontology we developed was named as human behaviour in fire evacuation ontology (OntoHBFE). Specifically, all the concepts involved in the domain knowledge are divided into three categories: classes, instances and properties depending on their attribute and scope. Classes are the focus of most ontologies, which can have subclass that represent concepts that are more specific. Basic concepts including factors, user, activity and scenarios are represented in the form of classes. All the main factors that affect user performance in experiment are organised as “Factor” class with three sub-classes: human factors, building factors and emergency factors. The “Activity” class consists four sub-classes representing user actions in four stages in fire evacuation from perception to translation and finally making and following decision. Various activities are described in each sub-classes in the form of instances, for example, in stage 2 translation users have different reactions with emergency situation such as observe, estimate, talk and wait. Figure 4.41 demonstrates the class hierarchy of OntoHBFE ontology.

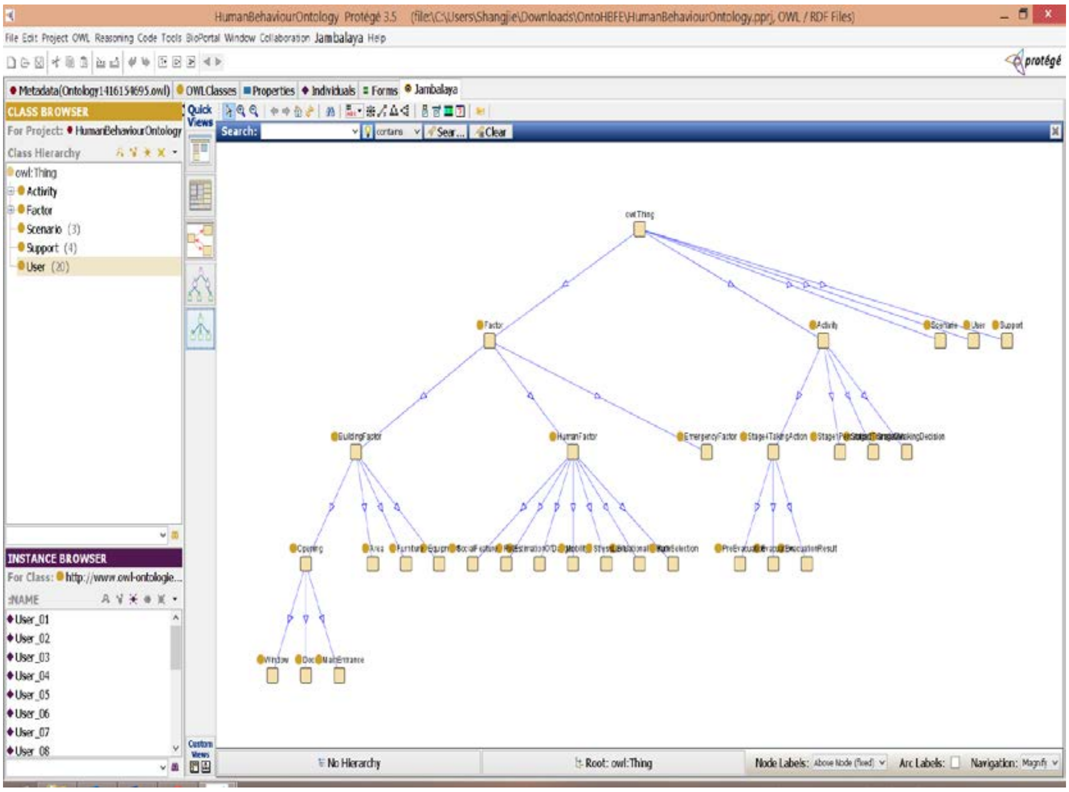


Figure 4.41 The class hierarchy of OntoHBFE ontology

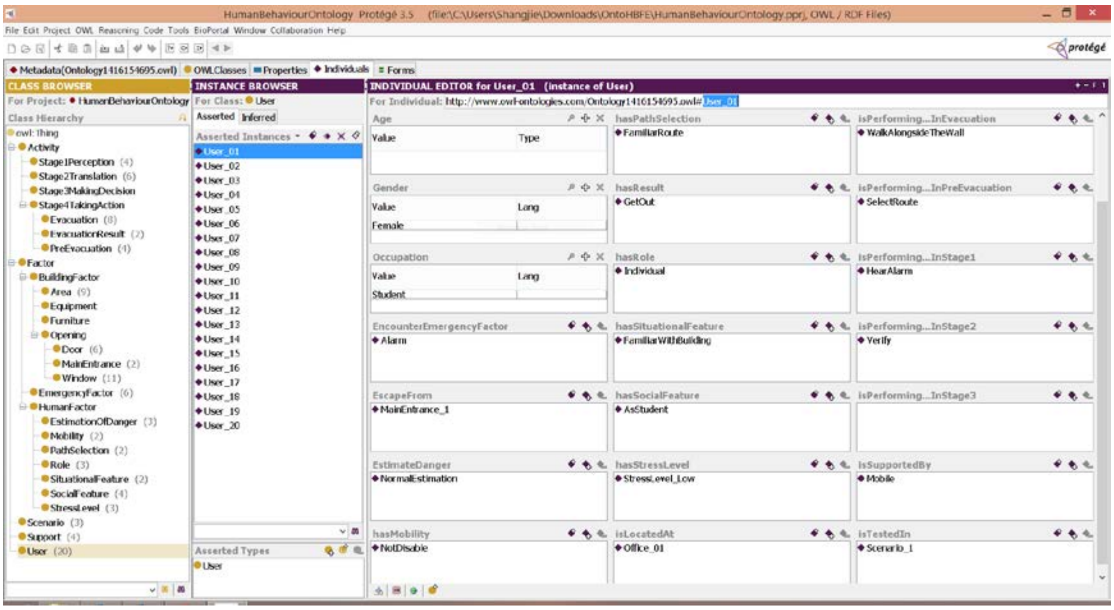


Figure 4.42 The example of User_01of OntoHBFE ontology in Protégé 3.5

In the class of "User", a group of instances represents all the participants involved in the experiment. In order to connect "User" class with factors and activities, the properties of ontology are introduced. There are three types of properties in

OWL-ontology: object property, data-type property and annotation property, which are used to describe relationships, define attributes and add explanations respectively. Taking the “Area” class (a sub-class of building factor) as an example, the object property “isLocatedAt” is defined in ontology to establish relationship between “User” and “Area” by adding “User” as domain of the property and “Area” as range of the property. Similarly, the other classes could be connected with “User” class by defining different object properties. Some other attributes of users such as age and gender (human factor) can be represented using data-type properties. By creating instances of “User” class, all the profiles of experiment participants and their behaviour while interacting with fire evacuation factors are recorded in OWL ontology model. Taking User_01 as an example which is shown in Figure 4.42, this instance describes the user “User_01” who was initially located in an office “office_01”, evacuated from the building as an individual assisted by mobile device and escaped from main entrance. Corresponding reactions and activities conducted by this user are in every stages of evacuation are specified in the instance editor of Protégé and demonstrated in Figure 4.43.

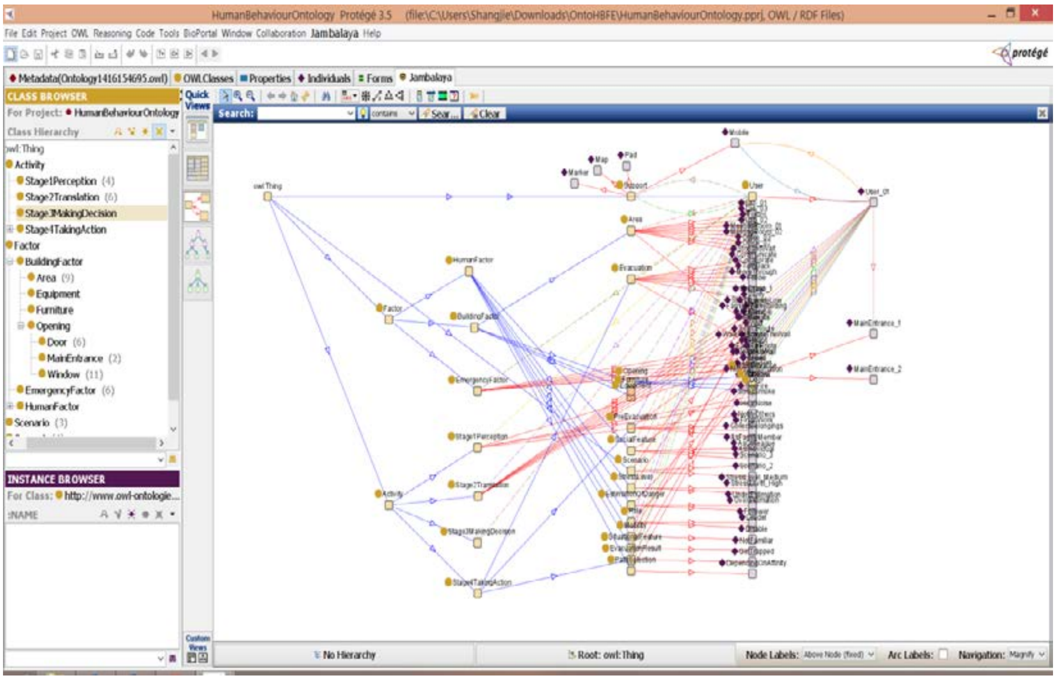


Figure 4.43 Corresponding reactions and activities conducted by User_01 based on OntoHBFE

Typically, the researchers create a few definitions of concepts in hierarchy and then continue describing properties of these concepts and so on. After defining classes and arranging the classes in a subclass-superclass hierarchy, it is time to define the property and fill in the values for properties for instances in the ontology. All the participants' background information and emergency behaviours are recorded in the OWL ontology, and this ontology modelling is completed and available to serve as knowledge base to game engine for simulation.

The simulations that refine emergency plan in the BIM-VE employ two main areas of knowledge engineering, namely ontological representation of existing information and semantic building information, which would be the key for agents to understand energy consumptions, emergency simulations, different servers and clients, different data formats, different computer hardware systems, different communication middleware etc.

According to real-time enquire ontology modelling, the agent (i.e. virtual character) can understand building information, understand different simulations to pair with building information and understand operation systems with different hardware and software to invoke the appropriate executions etc. Referenced semantic building information obtained from Revit client plays critical role in keeping the synchronisation of both geometric and semantic information by comparing different semantic information sets between different servers and clients. Take the simulations during a fire emergency for a test, player agents are distributed to different parts of Cardiff Engineering School model and can understand emergency situation (partly decided by semantic information related to unusual consumption of energy) with the help of knowledge engineering (Figure 4.44). The simulations of these player agents can help end-users find huge energy use areas that might cause emergency situation, and detect conflicts of a building design for emergency plan (such as narrow corridor for evacuation). These simulation results can be collected to refine building energy and emergency plans according to existing standards or guidelines.

Figure 4.44 The player agent simulation during a fire emergency to refine building energy and emergency plans

Chapter 5 System Testing

5.1. Generic human and BIM-VE interfacing testing

The BIM-VE provides multiple interfaces to get wider array of end users involved in BIM design environment to research their fire evacuation behaviour. These various interfaces are more beneficial and easier to use than a traditional design interface, for viewing and designing building information models (Appendix C- Experiment Results for Usability and Evacuation). The BIM-VE also has more potential to generate dynamic vivid emergency environment to accurately explore fire evacuation behaviour in the virtual environment, which is described in Chapter 6. This is achieved provided that a two way information channel is developed to overcome particular issues such as avoiding the distraction and scenarios anticipation of end users (i.e. the participants of experiments) in virtual experiments.

Specifically, the BIM-VE provides two desktop interfaces (i.e. first person/free view standalone and web-browser based versions), one modern mobile device interface (e.g. tablet and mobile phone), and two innovative Virtual Reality ('VR') interfaces (i.e. head mounted display and 3D projector versions). The general end-users can choose the interface they are familiar with. As for the researchers, they can allocate the appropriate interface to explore the human fire response within the virtual environment. The Unity3D server connects to Autodesk Revit plugin to extract building information to generate a dynamic virtual environment and synchronizes this environment with different interfaces for various purposes, which is shown in Figure 5.1. The end users as the experiment participants can carry out specific user-centred tasks within the virtual environment generated by Unity3D server. When emergency evacuations or events occur, their performance can used to explore the potential human behaviour during the emergency. Details as well as planning theories and reasons that contributed to the experiment procedure are outlined hereafter.

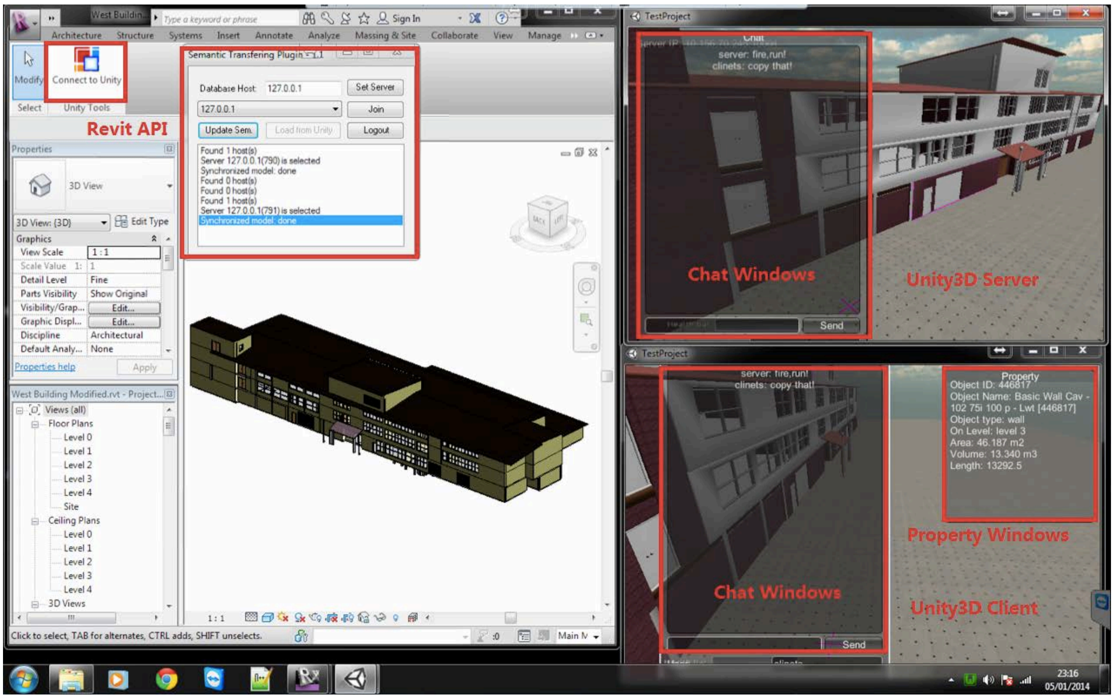


Figure 5.1 Autodesk Revit plugin to extract building information to the BIM-VE

First person/free view desktop interface: The output and input devices are constructed of a desktop monitor, mouse and keyboard. For first person view, the end user controls an avatar, changing direction and perspective view by moving the mouse, pressing W,S,A,D for forwards, back, left, right respectively and space bar to jump. The movement is bound to floor levels and stairs and blocked by barriers such as walls and other evacuees (Figure 5.2). For free view, the end user controls a camera view, changing direction by holding the middle mouse button whilst moving the mouse, travelling forward and backward by scrolling the middle mouse button and panning up, down, left, right by pressing W,S,A,D respectively. The view provides free movement through the 3D space unrestricted by any boundaries in the model. Both of the views offer a perspective 360° of horizontal and vertical rotation and can toggle function menu by pressing ‘Ctrl’ button.

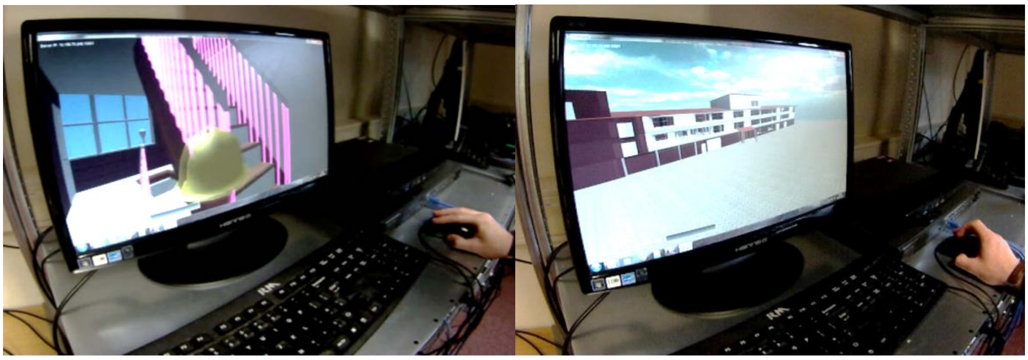


Figure 5.2 Desktop First Person (Left) & Desktop Flight Interfaces (Right)

First person/free view web-browser based interface: The support devices and controls are same as the desktop version, but the end users can get access to the system by typing the IP address in any web-browser that is connected to network (Figure 5.3), which can significantly increase the number of users involved in a BIM design environment, accessible across the internet.

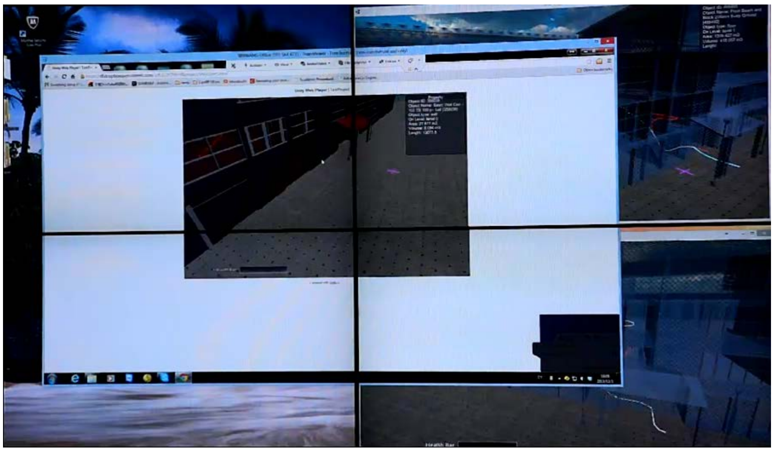


Figure 5.3 Web-browser based interface of the BIM-VE

Mobile device interface: The touchscreen mobile devices include smartphones and tablets running IOS, Android, Blackberry, and Windows operating system. The end users control an avatar by touchscreen, changing direction and view with a right analogue pointer, moving forwards, back, left and right with a left analogue pointer. The avatar can jump with a right function button and toggle the function menu by touching a left function button. This interface provides a first person perspective, 360° of rotation, vertical and horizontal view. The movement of the avatar is bound to floor levels and stairs and blocked by barriers such as walls. See Figure 5.4.

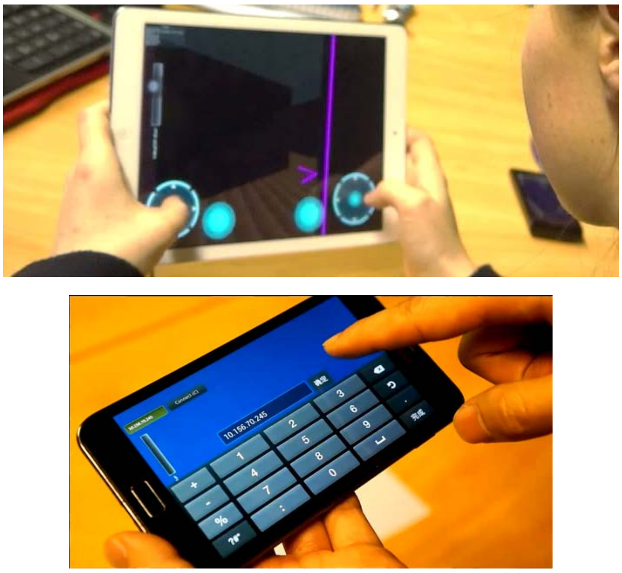


Figure 5.4 Mobile device interfaces

Activate 3D Projector with Razer Joystick Interface: This interface equips with a polarised light projector, 3D glasses and Razer Hydra Joystick. The user controls a camera view with a pair of simulated hands, using a thumb analogue stick on the right-hand controller to horizontally move forward/back/left/right, travel direction is controlled by rotating the left-hand controller relative to a table mounted sensor in front of the user. Vertically rotating the left hand controller works with movement by the right-hand controller to assist vertical movement. The interface provides a highly immersive 3D effect, perspective 360° of rotation vertical and horizontal view, free movement through the 3D space unrestricted by any boundaries in the model. It also provides some interactions between end-users and building model such as moving building objects from one place to another and showing the building information in real time, which is shown in Figure 5.5.

Figure 5.5 Activate 3D Projector with Razer Joystick Interface

Kinect with HMD Interface: This interface is constructed of the Windows Kinect motion sensor and Sony Head Mounted Display ('HMD'). The user utilizes the Windows Kinect to control an avatar, changing direction by rotating their shoulders, walking and running with slow and brisk swinging of their straight and bent arms respectively. The interface provides more immersive person 3D effect, perspective view limited to 360° of horizontal rotation, with a camera position set back from the avatar. Movement is bound to the ground floor only and unrestricted by any boundaries in the model. See Figure 5.6.

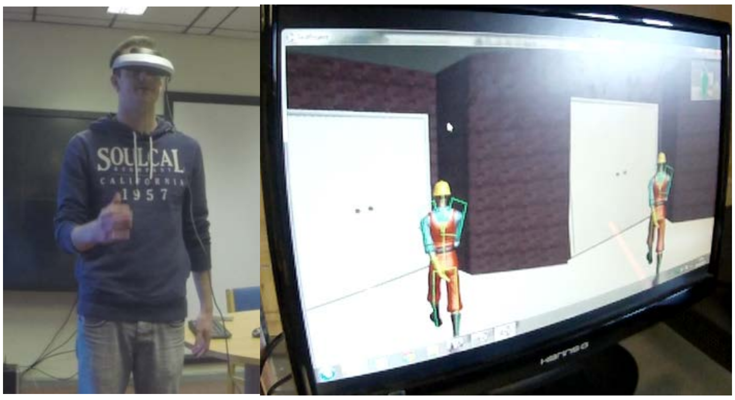


Figure 5.6 Kinect with HMD Interface

There are more than 70 classes defined to handle interfaces and utilities of system components to enable the application of bi-directional information flow between BIM and game. The interaction between the main classes contained within different system components are expressed in Figure 5.7. Specifically, the system contains five encompassed packages utilized by different applications or platforms. The Revit application utilizes classes of the Revit package to extract semantic information and add a control toolbar to the Revit interface (API). The 'ServerInteraction' class is used to send and receive data from the system server, which implements the 'UnityServer' class. Unity desktop package contains generic classes required by the server to provide tools for building review, design and management based on the data component. Other packages contain several common classes that are added into Unity clients for interaction with serious game in different platforms, i.e. a mobile platform, a web platform and other unity-supported device platforms.

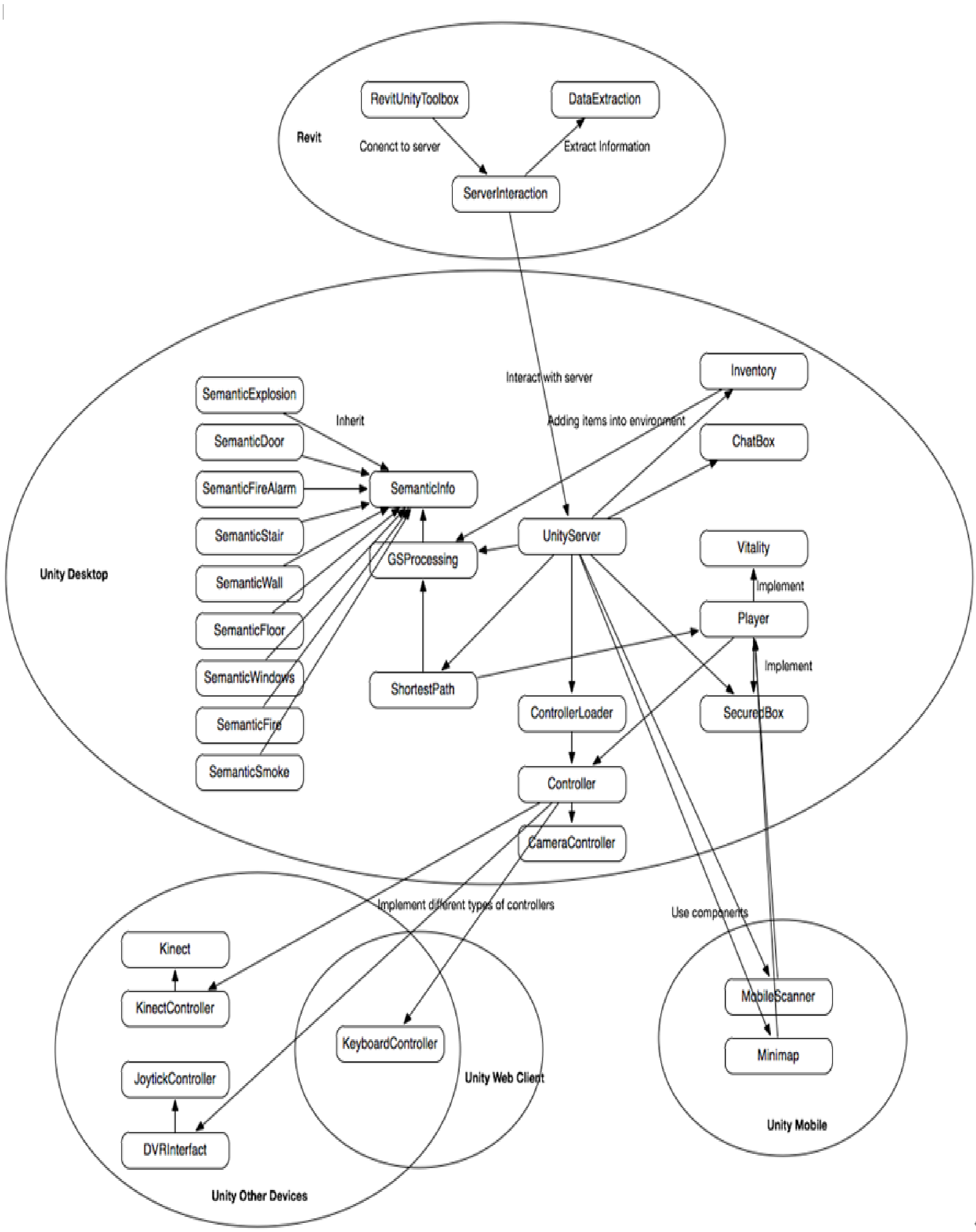


Figure 5.7 Interactive diagram of main classes for applications of the information channel

Five alternative human-computer clients have been provided in Cardiff University VR lab, which are desktop (first person/flight) client, web browser client, 3D Projector with Razer Joystick client, Kinect with HMD client, and tablet client. The major difference between the various clients is the input controller. Therefore, there are several classes inherited from the 'Controller' class to implement different interaction with the building information in the serious game. The 'KeyboardController' class in a unity desktop/web client inherits from the 'Controller' class to implement keyboard and mouse input in a desktop/web browser, while the 'MobileTouchController' adds touch buttons and wheel buttons on the mobile screen to control the movement, view of player and menu functionality. The 'DVRInteraction' uses the MiddleVR library to control player. It includes a 'JoytickController' class to implement several human actions such as picking up and moving items, and creating shortest path etc. in the building information model. The 'KinectController' class implements gesture detection functions by utilising the Activate3D library. Another difference between the platforms is the output method (i.e. using Monitor, HMD or 3D projector with glasses). BIM-VE automatically loads the appropriate view by MiddleVR plugin.

Test results - The engineering school of Cardiff university were chosen as the tested model because of its complexity layout on one hand and its uncertain use pattern on the other, which can provide a comprehensive and agreed-on data set for fire emergency evacuation and planning. The systems tested include the prototype of the two-way information channel and its applications on several user-centred tasks for fire emergency evacuation and planning. The application integrates with the middleware of the virtual reality hardware and software through APIs to combine the virtual and real worlds; the agents in the system executing accurate evacuation simulations according to the requirements of the end-users and the ever-changing building information; the Unity3D server utilises geometric and sematic building information to dynamically change scenarios and keep participants focused on the virtual tasks or training.

To achieve virtual immersive environment, activate 3D projector with razer joystick interface equips with a polarised light projector, 3D glasses and Razer Hydra Joystick. The user controls a camera view with a pair of simulated hands, using a thumb analogue stick on the right-hand controller to horizontally move forward/back/left/right, travel direction is controlled by rotating the left-hand controller relative to a table mounted sensor in front of the user. Vertically rotating the left hand controller works with movement by the right-hand controller to assist vertical movement. Kinect with HMD Interface is constructed of the Windows Kinect motion sensor and Sony Head Mounted Display ('HMD'). The user utilizes the Windows Kinect to control an avatar, changing direction by rotating their shoulders, walking and running with slow and brisk swinging of their straight and bent arms respectively.

A total of fifty individuals took part in the test, each using the four different Unity3D interfaces (including five modes and web-browser based interface was regarded as the desktop interface) to finish basic user-centred tasks and complete a pre-experiment and post-experiment questionnaire. The average response was recorded for analysis except for situations where there was a clear bi-polar response when analysed individually. Figure 5.8 shows the average time taken for each participant to (1) become familiar with each interface, (2) to follow the guidance path to position objects in a specified room, (3) and average number of times assistance requested.

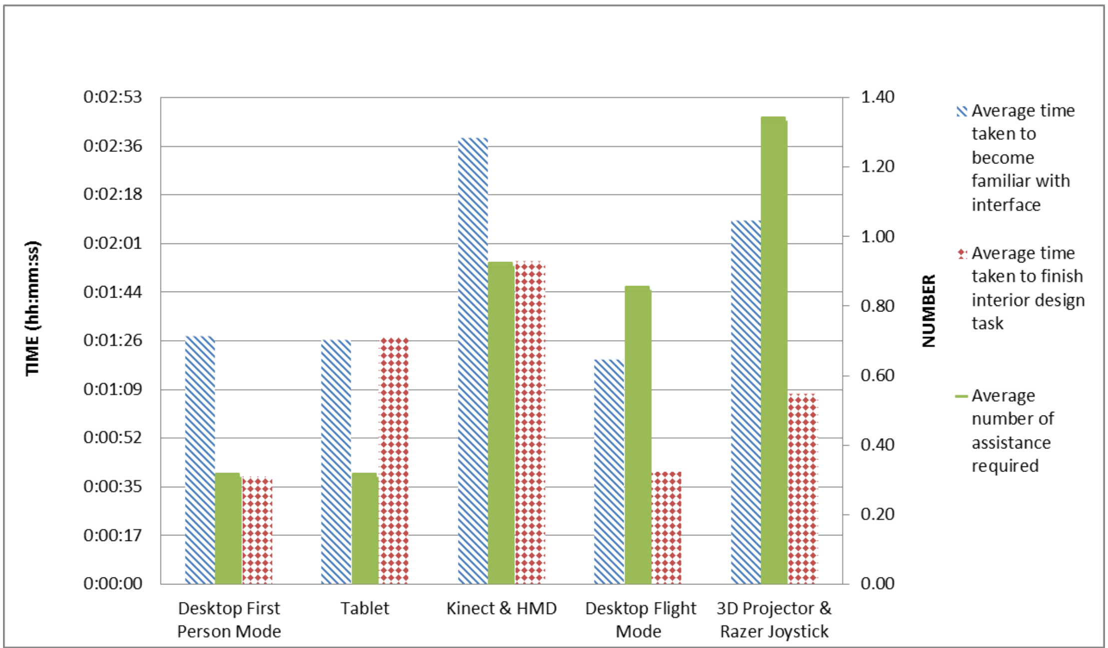


Figure 5.8 Recorded test results for evaluation of easy-to-use

These tests are intended to represent how intuitive and easy to use each interface is, which in summation should interpret how user friendly each interface will be for general end users. The two desktop and tablet interfaces are similar in terms of time taken to become familiar with the interface, whereas the 3D Projector with Razer Joystick and Kinect with HMD respectively took 52% and 86% longer than the average of the other three interfaces. Again both desktop modes proved to be the quickest when finding objects and designing building interiors under supervison in the model whereas despite its similarity in terms of intuitiveness, the tablet interface took 126% longer than its desktop counterparts. The 3D Projector with Razer Joystick performed better taking 74% longer but all performed better than the Kinect & HMD system which took 195% longer than the two desktop interfaces.

However, regardless of the time need to geting used to the clients, time taken to carry out a user-centred tasks were below 3 minutes, which is substantially shorter than learning traditional engineering software to finsh a similar design task. Normally, it would take several hours to several days (depending on individual ability) to learn the basic functions of professional engineering software to perform similar design tasks on professional engineering software.

The average number of assistance-requests was very low for the desktop first person mode and tablet interfaces at 0.31 times for each, the Kinect with HMD and desktop flight mode where higher at 0.92 & 0.85 times respectivelly which averaged between the two gives a 185% increase. The 3D Projector with Razer Joystick had an assistance request rate of 329% higher than the desktop first person and tablet interfaces. Although the number of requests varies largely between different clients, they were all less than 2 times. It is highly unlikely that an individual would need to learn to operate professional BIM software with such minimal levels of assistance required.

The participant post-questionnaire responses further expanded on the differences between each interface focusing on manoeuvrability, immersive feeling, realistic feeling, quality of model representation and level of interest / excitement (Figure 5.9). Clearly the greatest difference between the interfaces was in manoeuvrability. The Kinect with HMD system scored a low 2.67, equating to a median between ‘Difficult’ and ‘Very Difficult’ on the response scale. There is then a significant jump to the 3D

Projector with Razer Joystick system at 4.38, landing at the moderate side of 'Difficult' and then another significant jump to the tablet interface which scored 6.67 on the moderate side of 'Easy'. The two desktop interfaces came in as clear preferences above 'Easy' which was marked as 7 on the response scale; the flight mode beat the first person alternative by 0.42 points. It seems that time is needed for end-users to adapt to the BIM-VE clients with ad hoc virtual reality devices that are not present in their usual life.

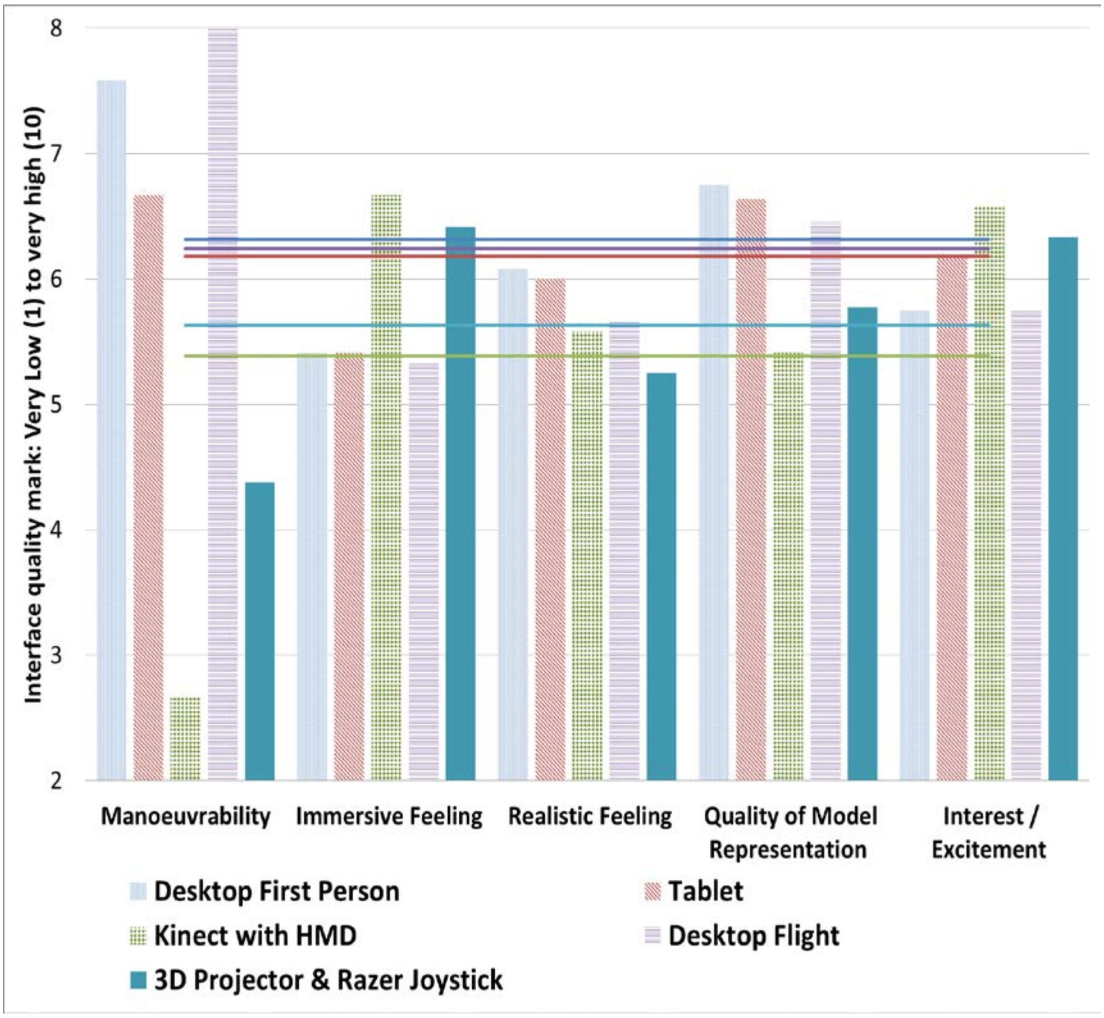


Figure 5.9 Post-questionnaire response – interface qualities

There is a slight difference in results for immersive feeling. The tablet and two desktop interfaces showed almost zero differences in immersive feeling whereas there is a noticeable 1.155 average increase with the two virtual reality ('VR') interfaces, with the Kinect and HMD interface topping the 3D Projector and Razer

Joystick system by 0.25 points. It is clear that clients with high quality virtual reality devices can immerse the participants into the virtual environment although the participant requires more time to become familiar with these client devices. In terms of the realistic feeling and quaility of model representation, the participants tended to give the clients they are familar with a higher score. VR clients seemed less popular in these two catagories. This is possibly due to people prefering to use methods they are familiar with or that the current VR develpments do not satisfy the participants' requirements (e.g. quality of model representation).

Finally, interest / excitement saw both desktop versions achieving the worst score, with the tablet interface scoring noticeably higher by 0.42 points closely led by the 3D projector with Razer Joystick system, all being rated lower than the Kinect & HMD system. This is because the more accurate details a VE can map with the real via VR devices, the more immersive effects the end users can feel. It demonstates clearly the VR clients of the BIM-VE hold a huge potential to be popular in the future. In addition, the refresh rate and judderless head tracking also pay very important role in higher immersion.

Because the BIM-VE aims to get the end users involved in the building design process, the post-questionnaire investigated which interface is preferred to be accessed by participants in daily life. Figure 5.10 clearly shows that the mobile interface of the BIM-VE became the most popular one with the development and proliferation of current mobile technologies. The desktop interface was also welcome because it is esay for most participants to adapt themself to this traditional design envrionment. There is no surprise that most particpants did not choose two VR interfaces as the daily used interface, because these two interfaces needed to work with specific virtual reality devices those were not common in daily life. As for web interface, it was still under development and based on a web link generated by Dropbox. The link address was too complex to be remembered by participants. This problem can be solved if we build a server to specially hold the web interface of the BIM-VE.

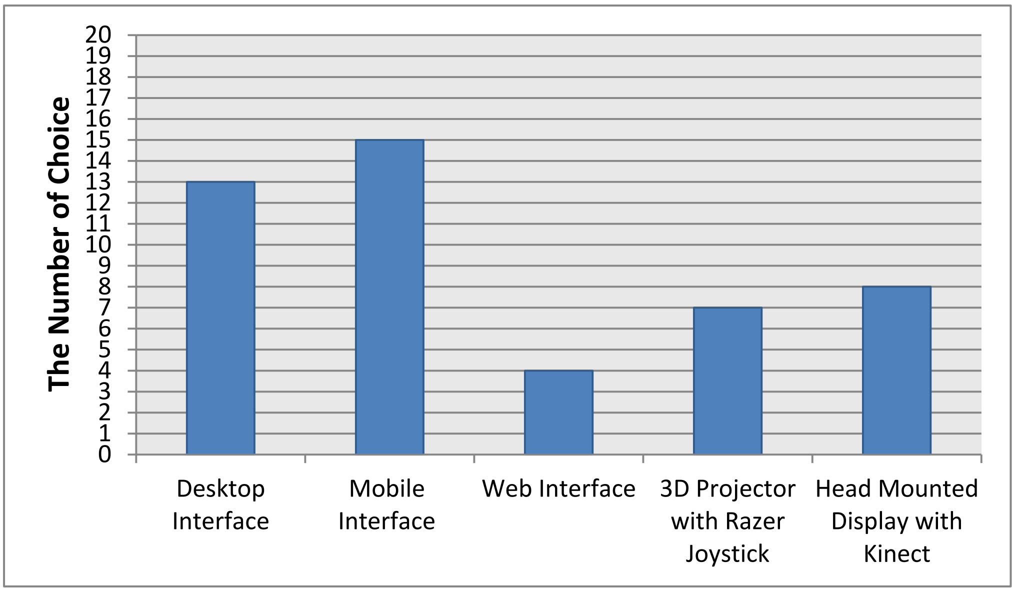
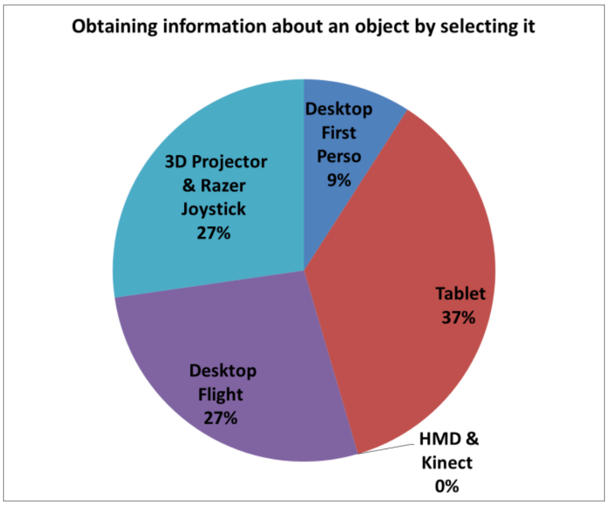
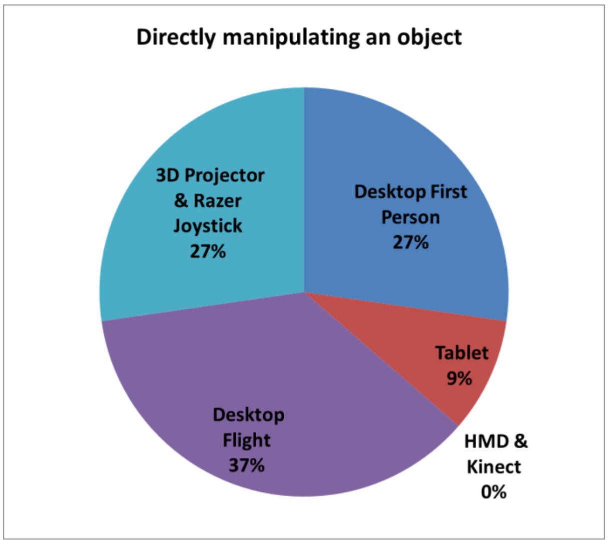


Figure 5.10 Which versions are preferred to be accessed in daily life

To obtain a more direct preference from each participant, they were asked which interface would best suit the common functions they would be involved in activities including client consultation and everyday engineering work; the results of which are shown in Figure 5.11. The Kinect & HMD clients held no preference in any task involving significant input to the system, only preferred by some for following path guidance to get familiar with building layout. The two desktop clients had a strong preference in the responses with the flight mode achieving particular preference ‘obtaining building information by selecting objects’ task. The interaction tasks had a strong response towards the 3D Projector and Razer Joystick. The mobile interface had major preference in the ‘being familiar with building layout’ tasks but a much lower rating in the ‘direct manipulation’ task. The current condition of each interface may be far from the true potential each technology has when applied to BIM depending on the correct combination and programming. Future work needs to investigate what features swayed preference between each interface, how each interface could be made better and ultimately which would be superior if every performance factor was optimised through product development.





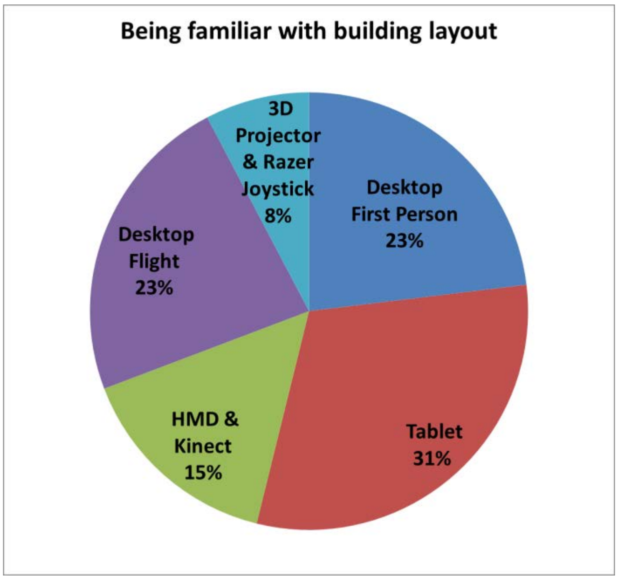


Figure 5.11 Preferences between interfaces for common functions of the engineering work

The BIM-VE integrates virtual reality technolgy to provide advanced fuctions for fire emergency evacuation and planning both in real and virtual world. Although some of these functions are under development, it is clear that the BIM-VE bring more benefits comparing to traditional design and managment methods. Figure 5.12 shows the result of post questionnaire investigating how beneficial the participants can get from advanced functions of the BIM-VE in contrast to traditional techniques. It can be seen that the particpants were generally satisfied with current advanced functions (the average mark scores for every advanced function are all above 5-beneficial) although these advanced functions were still under development.

Based on building information extracted from Revit, the BIM-VE can further utilize VR technologies to allow the users to get real time services such as obtaining building information and finding detinations in both real and virtual world, which were obviously accepted by participants (the average score is above 7). The available functions of immersive building interior design and user-centred design are limited and under development. However, most participants believed this can allow them to personalize a building design from their perspective and attempt a walkthrough before the building design was decided upon, which can fulfil the concept 'design and try it before you buy it'. Therefore, the score of these two functions was above 6.7. It is reasonable that the score of real-time design clash detection was a little bit lower (6.5) than the others, because this function was too specific for most participants who were not from AEC field.

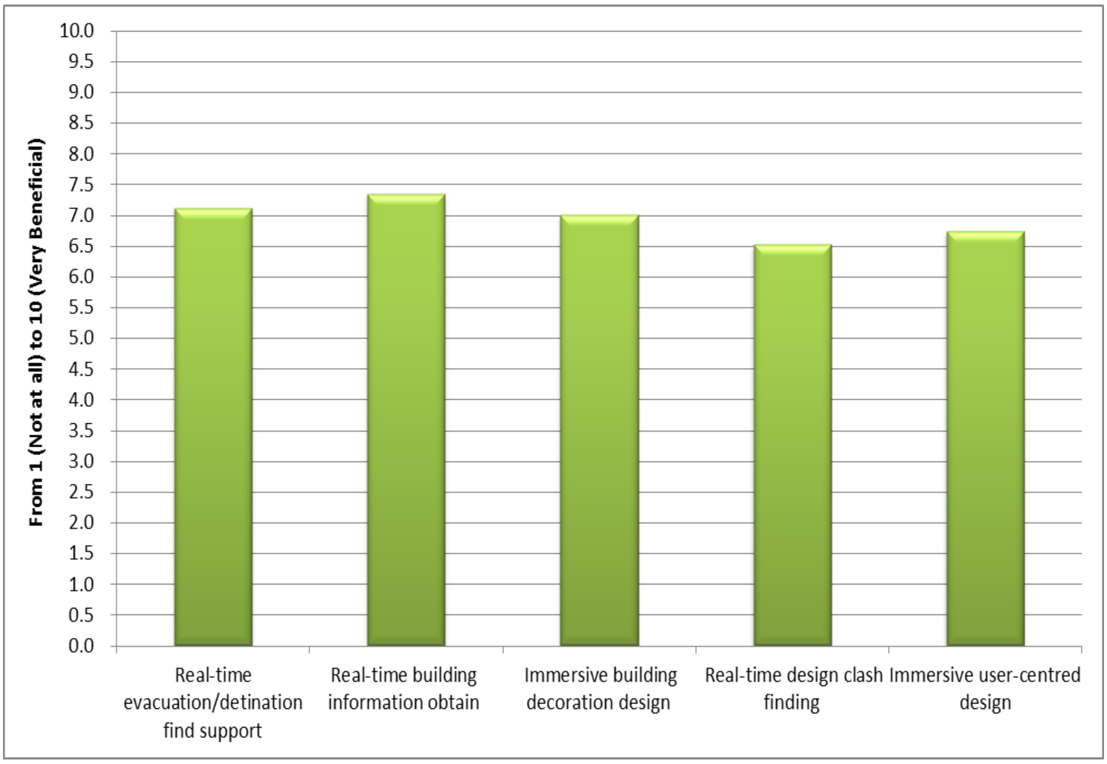


Figure 5.12 How beneficial participants can get from the BIM-VE comparing to traditional techniques

The reason why the BIM-VE provides multiple interfaces is to get more end users (including both general end users and professionals) involved in building design and management. Throughout the building life cycle, the end users can be simply divided into three categories: clients buying or using the building; stakeholders selling the building; architects or engineers designing the building. Although most participants were students, they were studying a wide range of subjects such as engineering, sciences, mathematics, business and media, which can potentially cover the aforementioned categories.

Figure 5.13 demonstrates the preference of participants about different interfaces of the BIM-VE as a ‘client’, ‘stakeholder’ or ‘architect or engineer’. Specifically, the participants were willing to walk into the building as they can in the real to see the inside of building, which is the reason why the desktop interface (flight mode) is not popular. Many of the participants chose the use desktop interface because were more accustomed to the use of traditional desktop as clients. With fast developing and adoption rates of mobile technologies, smart phones have become very common. Therefore, the participants liked to use mobile interface. As for the two VR interfaces, although they were still under development, they impressed participants with its immersive capability and was received very well by most. As the stakeholder, the choice is similar to that of the client. However, it should be noticed that the mobile interface became the most popular interface, mainly due to a greater need for mobility and simplicity.

Desktop interface (especially flight mode) turned out to be the preferred for ‘architect and engineer’, because it is very similar to the current design environment of most commercial design software. The number of participants who liked Razer Hydra Joystick and 3D projector interface followed the result of desktop interface. This might be because the VR interface was easier to use and can provide immersive 3D design environment to the public. In contrast, HMD and Kinect interface can only provide high definition immersive environment to one person and end-users require more time to get accustomed to motion tracker sensor, which is the reason why this interface was not welcomed by the ‘architect and engineer’ category.

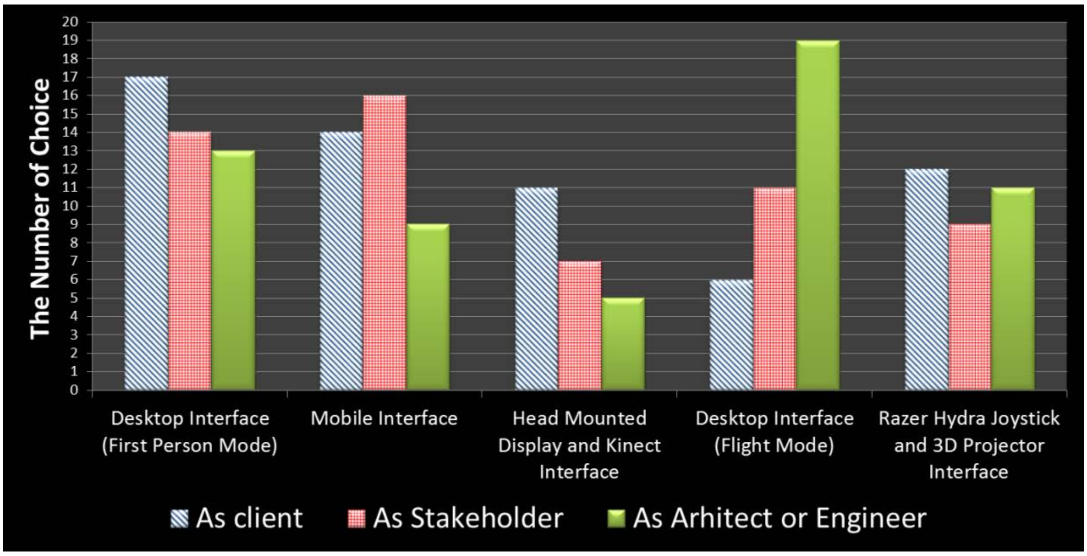


Figure 5.13 Which interface would be more effective as a 'Client', 'Stakeholder', 'Architect or Engineer'

Characteristics were recorded in a pre-questionnaire that may determine differences between the tested clients including: subject studied or area of work, computer game experience, experience at using devices before hand, experience using modelling software, knowledge of engineering school west building and alertness when participating in the experiment.

For example, participants who were studying or working in an engineering field, illustrated in blue graphics in Figure 5.14, appeared to take longer to feel comfortable using each interface than those not studying or working in engineering areas. The two VR interfaces (i.e. Kinect & HMD and 3D projector & Razer joystick) were utilised better by those not in an engineering field whereas the desktop flight mode was found to be more suitable for engineers. Engineers also appeared to ask for more assistance, but this increase was at an insignificant level across most interfaces except the Kinect & HMD interface.

Across the remaining characteristics there was more influence on the participants' ability to perform user-centred tasks than familiarisation rate and number of times assistance was required within the BIM-VE. Familiarisation rate improved with "level of alertness". This improved slightly with experience of using BIM but only on the desktop interfaces. It was also noted that the desktop flight mode showed a better familisation rate when the participant has experience with 3D software, BIM software and familiarity with the engineering west building. The reason for these results might be because 'level of alertness' and 'experience of using 3D or BIM software' motivate the participants' ability to learn a BIM based extension performs design tasks, which is similar to traditional BIM software, or influenced by people who are familiar with the real environment (i.e. engineering west building). A stronger negetive trend is shown between hours playing computer games per week and time taken to perform a simple design within the BIM-VE. Indeed, it is easier to familiarize a gamer with the operation of the BIM-VE when it is based on a traditional Game Engine.

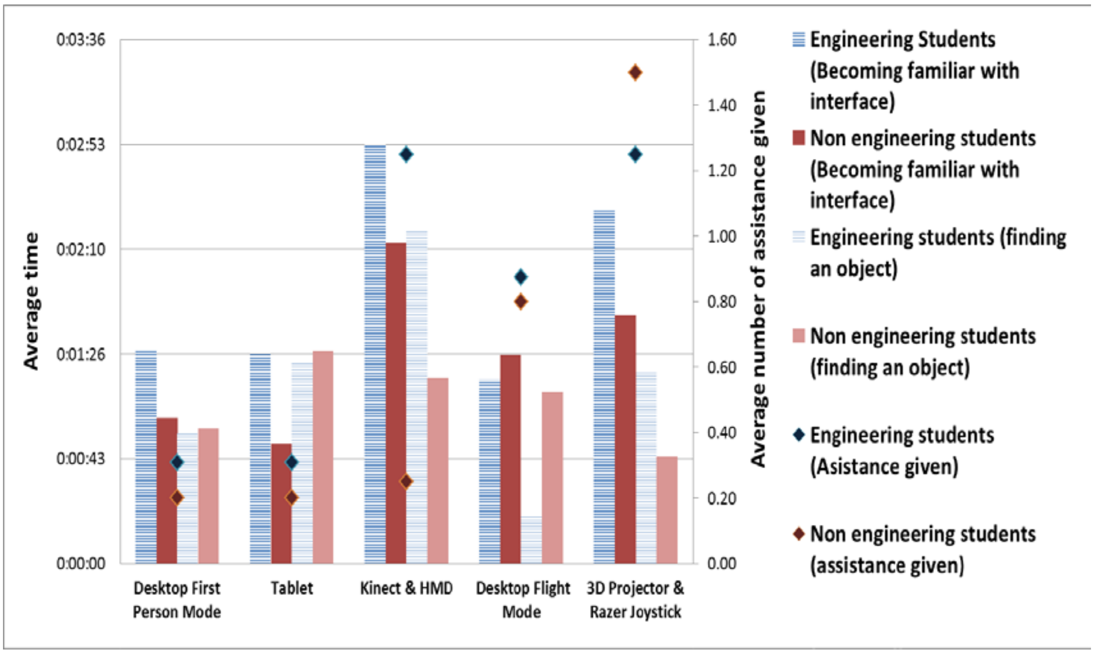


Figure 5.14 Effects of studying engineering

5.2. Case Study based functionality Testing

After the ease-of-use test, it can be said, the skills required to use the developed system can be learned quickly by different end-users from different backgrounds, although there are still some limitations that affect the leveraging of the system's full potential. The second level of testing is to validate the life cycle use of the developed system, which was explained through two specifically devised use cases covering building internal emergency design and emergency evacuation training/guidance. The process to carry out these tests in the dynamic scenarios is similar to descriptions in Section 5.1. Specifically, the details are demonstrated as follows:

- The administrator within Unity3D server creates a host/session that holds building information for building design and management. The two-way information channel then transfers both semantic information and geometric building information from the BIM to the serious game.
- Unity3D server loads the appropriate components with behaviour scripts through the scenarios based on the categorized library, which works with building semantic information to create dynamic scenarios for building design and

management.

- Unity3D server synchronizes dynamic scenarios with the Unity3D clients to allow general end-users and professionals to appear on the same platform though the network. The general end-users can choose the input and output devices of their client end use according to their requirements.
- Unity3D server and clients provide a communication system such as text message windows and audio / video gizmos to allow real time communication between players.
- For building internal emergency design, general end-users using Unity clients get the building design from the Unity3D server that extracts building information from professional BIM software (i.e. Revit). If the design professional is using the Unity server, the general end-users can express their ideas via using their client interfaces directly (which are linked to server end) to help achieve a better emergency plan design. The client interface has an easy-to-use graphical user interface (GUI) connected to the design library, and is supervised by the design professionals. After finishing the emergency design improvements, the professionals in the Unity 3D server have the authority to decide whether accept the changes and update the real model (i.e. to synchronize building information back to professional BIM software). If the professional is not present, the general end-user can still synchronize their building emergency design with attached notes with the Unity 3D server which allows the professional to check them at a later date.
- Similarly, in the scenario of emergency training and evacuation guidance the general end-users and the emergency manager connect to Unity 3D clients and server. The Unity 3D server and data components map building information collected from both the real and virtual world, providing the basis for building performance visualization. With the application of path finding algorithms and space representation in the BIM-VE, the emergency manager in Unity 3D server can provide players with real time emergency evacuation training/guidance on multiple platforms. The Unity3D clients have several functions to help users find the evacuation route such as resetting start and end destinations and locating position by

mobile scanning markers.

5.2.1. Two way information channel testing

The data component is the main part in building the two-way information channel, which automatically transfers geometric and semantic building information between the BIM model and the virtual environment, by means of the Revit API and the Unity3D server. No matter whether the building information in Revit or the Unity3D server was changed, the Unity3D clients would automatically update the corresponding visualization and simulations. The application of this two-way information channel has been preliminarily tested, with the aim to prove that the automatic bi-directional information flow between the BIM model and the serious game can save a substantial amount of time and money that is usually required to adjust the building environment depicted within the BIM-VE. The system provides a large potential for real-time building performance visualization and management with ever-changing building information.

The west building of Engineering School of Cardiff University was created in Revit as the representative BIM model, whose size is around 26MB and includes the detailed geometric and semantic building information for building emergency management. The Revit API which connects to the AMP system was installed to automate building information transferal between the BIM model in Revit and the virtual environment in the Unity3D server. The test of information transferring efficiency was carried out between two HP desktops utilising Microsoft Windows 7 64-bit operation system with Intel i7 quad core CPUs and 4GB ram each. The wireless network speed connecting the two desktops was up to 2 Mbps.

From the test it was found that the transferring process for a 26MB building model took 30 seconds, while the time to synchronize the building environment between the Unity3D server and the Unity3D desktop client took 1 or 2 more seconds. The BIM-VE supports multiple threads to accelerate building information processing, allowing information transfer from Revit to the Unity3D server and information synchronization between the Unity3D server and clients to be processed simultaneously. Therefore, the time to build the virtual environment is same as the information transfer time from the Unity3D server to clients because it always takes 1 or 2 seconds to finish synchronization process after the Unity3D server receiving building information from Revit. To validate the efficiency of this two way information channel, the size and details of the BIM model were changed and the time required to transfer the building information to build the virtual environment was recorded. The results are shown in Figure 5.15. It can be seen that a medium detailed virtual environment for building review and design can be generated in under a minute in the BIM-VE if the model size is around 40 MB. The information transferring speed depends on the speed of network and the client version of the BIM-VE. In addition, it is easy to use the comprehensive interface in Unity3D server to adjust the details of extracted building information for different purposes.

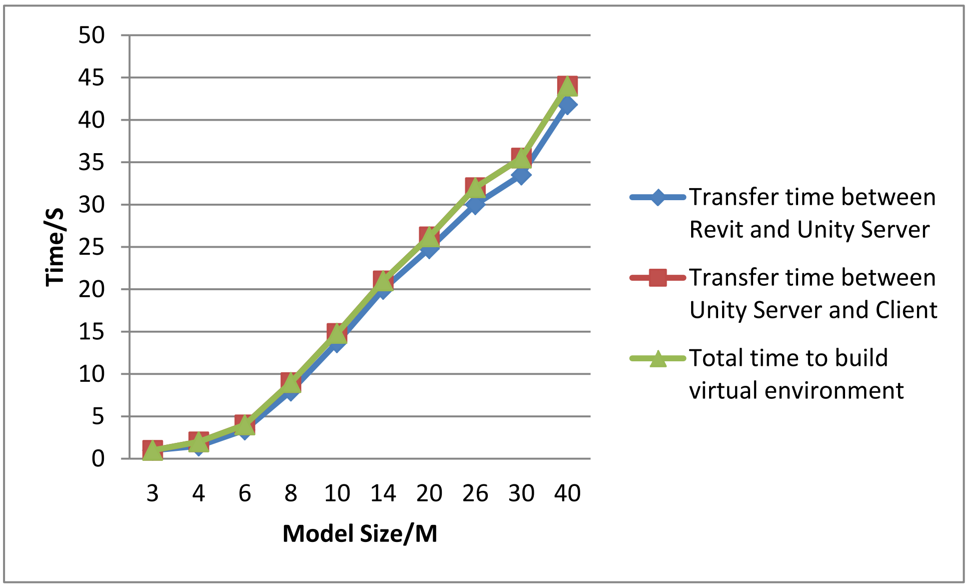


Figure 5.15 Test results of building the medium detailed virtual environment in the BIM -VE

If the building information in Revit is changed, the Revit API can transfer the updated building information (i.e. geometric and semantic building information) to the Unity3D server and clients in a very short time (depending on size of the BIM model). Similarly, the building information modified by the Unity3D server can also be reflected within the BIM model in Revit (if the server is authorised to do so by the professional designers using Revit). Figure 5.16 shows the overview of testing the two way information channel between Revit, the Unity3D server and the Unity client. There are some extensible functions such as the real-time communication (in the chat windows for both Unity3D server and clients) and building information visualization (in the property window if the mouse stays on the building components) to assist user-centred building emergency design and management in the BIM-VE. In terms of automatic bi-directional information flow, Figure 5.17 demonstrates the Revit API connected to the AMP system, building a simple bi-directional bridge between the professional BIM software (for the building designers) and the virtual environment (for the general end-users), which allows the involvement of the end-user in refining both the building design and energy/emergency plan. All the building information can be automatically transferred and updated between the BIM model and virtual environment by a single click on the function button of the Revit API (Figure 5.17), which provides the base to extend the functions of the current BIM software (i.e. Revit). For example, building geometric information such as a wall element can be deleted or added in either Revit or the Unity3D server, and a modified wall element can be synchronized in each system using the Revit API for the purpose of building design or building performance management (Figure 5.17).

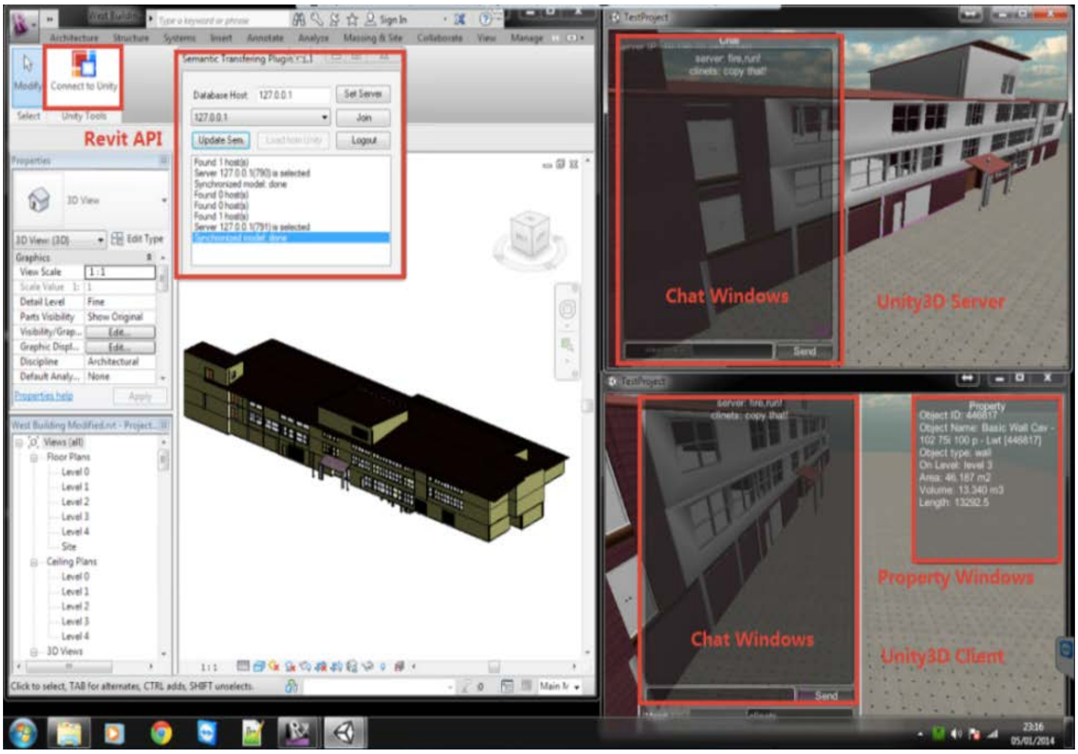


Figure 5.16 Automatic data transmitting between Revit, the Unity3D server and the Unity3D clients

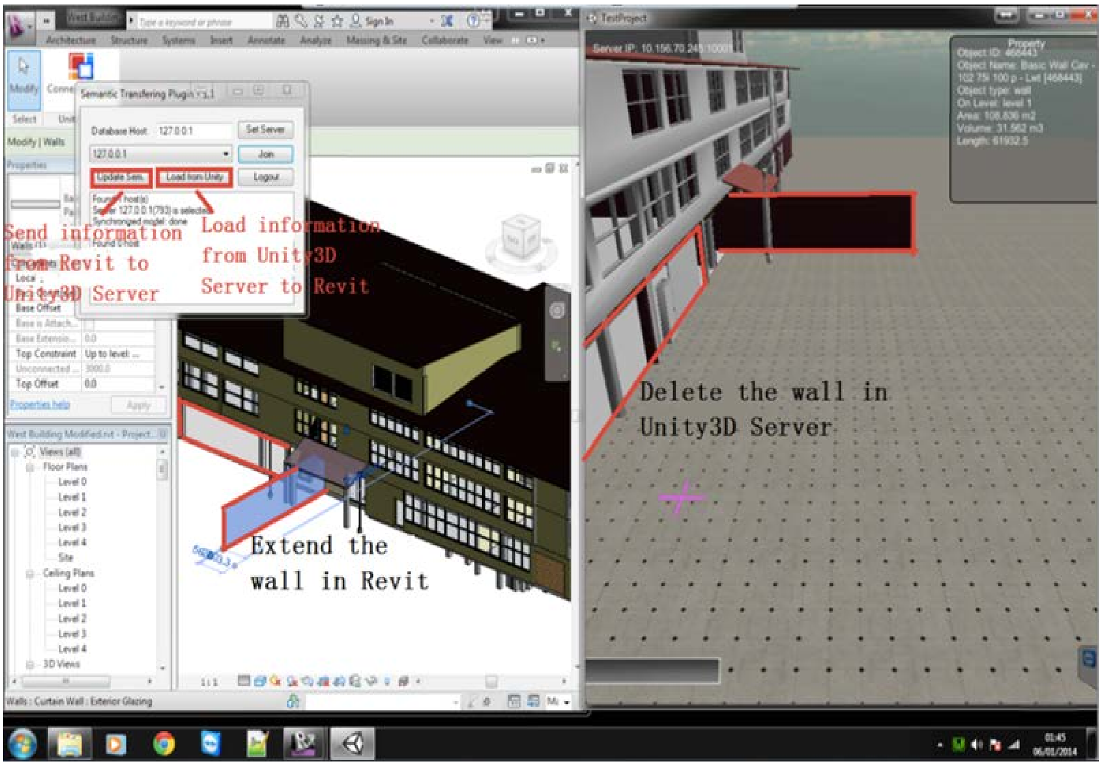
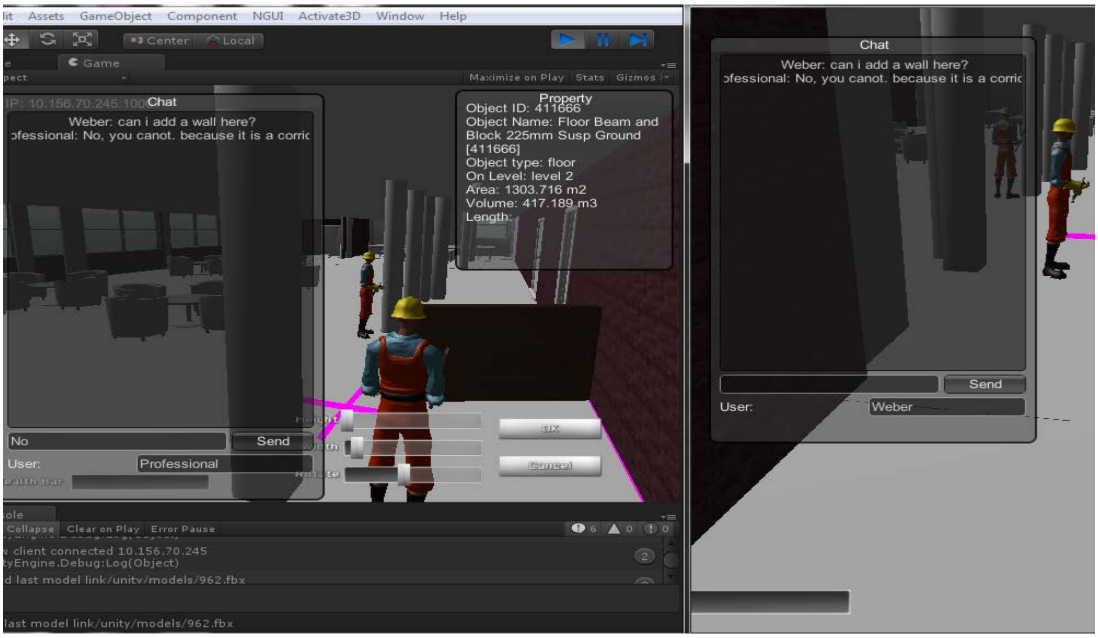


Figure 5.17 The bi-directional information transferral of the Revit API for building design

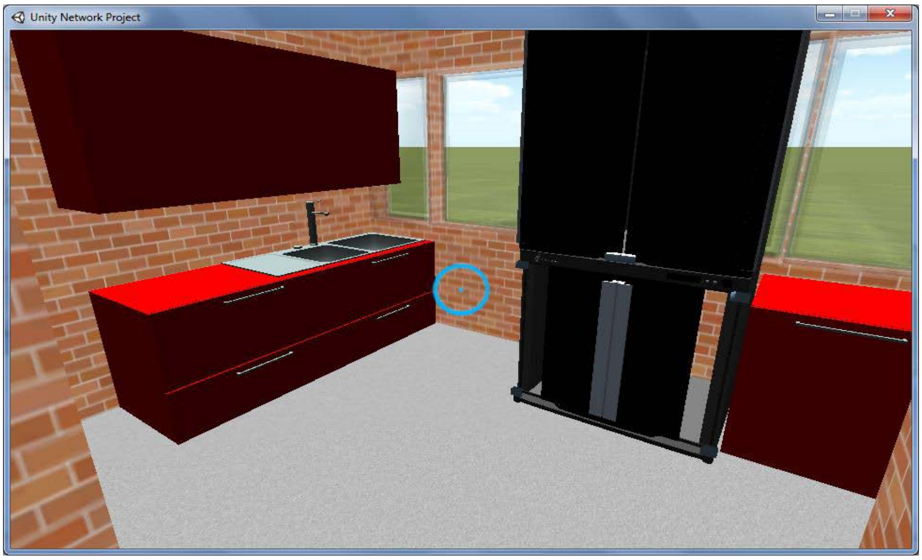
5.2.2. Dynamic scenario generation for building emergency design

Rationale: BIM-VE utilizes a library based approach to utilize building semantic information to generate the dynamic scenarios to keep the design participants engaged. On top of building emergency regulation, the inventory library to assist building internal emergency design is shown in Figure 4.34. Take the a residential room for example, the bathroom and kitchen components are shown in (a) and (b) respectively. The menus automatically adjust their size in relation to the current screen height. The general end-users only need to click on one of the menu items and place the selected object on the suitable position within the BIM-VE. Currently only limited menus were created (for the demonstration purpose) in the local computer for the scenario testing. However, the scope for expansion to meet particular tasks is wide if the library connects to a database to download the appropriate building components, e.g. to connect to the existing stand BIM component library.

Semantic information extracted from a BIM model is utilised to enhance performance of building internal design within the BIM-VE. The general properties of building objects (i.e. door, wall, and floor) are defined in '*SemanticInfo'*. Working with it, the place-able positions for specific items are referenced to the definition in '*SemanticPosition'*. For example, user cannot put a bath on the wall, but can place a mirror on the wall. The end users can also change the texture, colour and appearance of menu items to satisfy their ideas and perceptions, which are referenced to attributes defined in '*SemanticFuniture'*. Currently only limited menus were created in the local computer for the scenario testing. However, the menu can be limitless for general end-users if it downloads the appropriate furniture/building components from connected BIM component database.



(a) General end-users designing the building internal with the remote help of professionals



(b)Furniture placed in the tested building

Figure 5.18 User-centred building interior design

Design Testing: To achieve the user-centred building internal emergency design, the general end-user in Unity clients can use chat tools to exchange their ideas with design professionals or advisors within the Uniy3D server, and get involved in the building emergency design process to make the resultant interior design fit for purpose (Figure 5.18 (a)). Under the supervision of professionals, design mistakes that make the building unfeasible can be avoided while meaningful insight and input can be gathered. For example, they cannot remove a load bearing wall within the BIM-VE, but can adjust the position a wash basin to make it more accessible. With this user-centred design concept, the professional in the Unity 3D server can supervise the general end-user within the client, for example, place different elements of a kitchen within a test room to form their ideal room layout without influencing the building emergency plan (shown in Figure 5.18 (b)).

Because Unity3D desktop and web browser clients have the same functions with regards to user-centred design and review, they are grouped as a whole for the test. Therefore, three alternative Unity3D clients (as described in Figure 3.2) with five modes (as described in Section 5.1) can be used by general end-users to view and manipulate a building information model with guidance from design professionals using the Unity3D server. Thus user-centred design within the BIM-VE is achieved. The 'view and manipulate' tests form a fundamental part of most BIM activities. It allows end-users to be involved, and easy to use.

5.2.3. Dynamic path finding for real-time 3D fire evacuation

Rationale: 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 spaces, 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, it can provide a dynamic path finding simulation. The most important factors considered to influence path finding results include 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). Similar to inventory library for user-centred building interior design, the effects and tool library are incorporated into the Unity3D server for evacuation guidance (shown in Figure 5.19), with the objective to increase the efficiency of escape rate in the real fire disasters. The scenarios are dynamically generated (eliminating any anticipation of the fire emergency scenario), the environment can also be used for fire evacuation training.

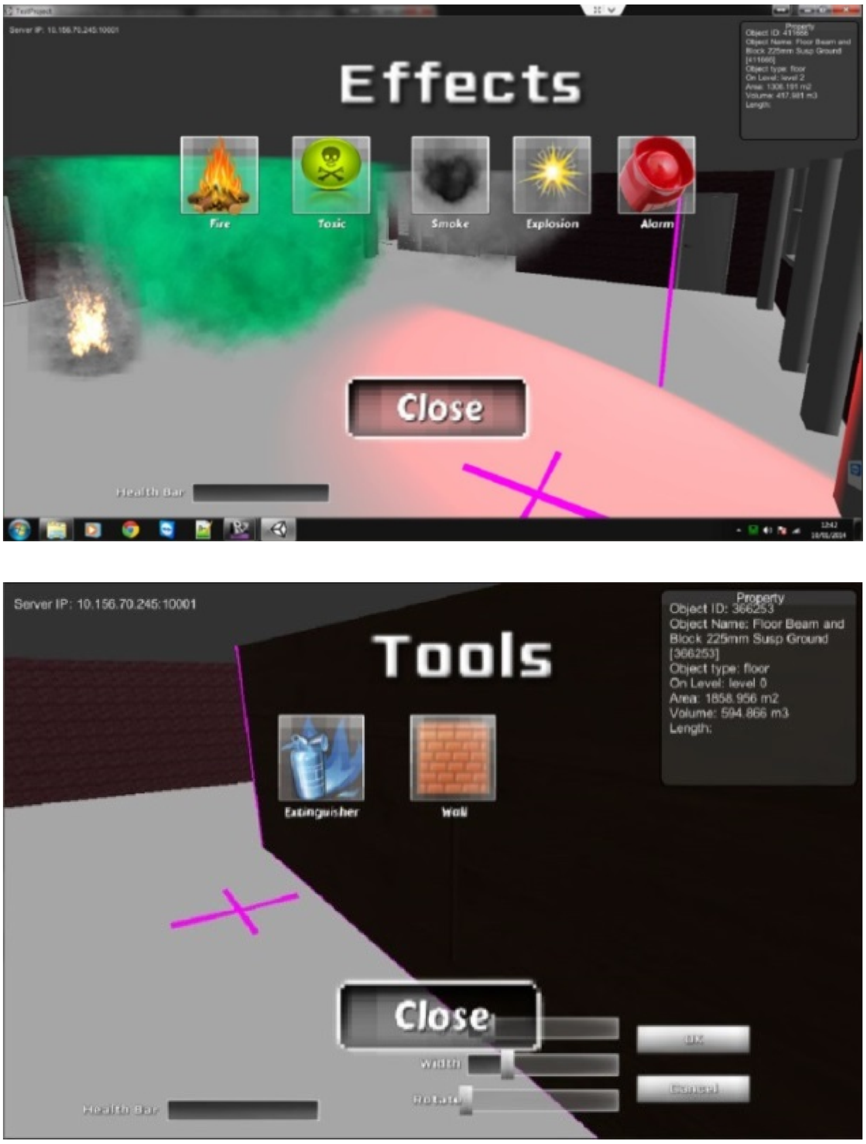


Figure 5.19 Effects and tool library to create dynamic scenarios in Unity server

The effect library: The effect library was used by the administrator of the Unity3D server to create unexpected events of fire, smoke, explosion, and alarm warnings to guide and train the participants' responses. These unexpected events work with building semantic information to create a vivid and dynamic building fire scenario.

Take for example the fire effect, which was added to the evacuation scenario in the Unity3D server with a specific time interval to create the dynamic spread of fire. 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.

Fire Alarm: In terms of the fire alarm, its semantic information in Revit is referenced to the object IDs of a set of fireproof doors, which close on activation of the corresponding fire alarm. 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 doors to prevent the spread of the fire while the shortest evacuation path in the Unity3D server is automatically updated for all clients (Figure 5.20 and Figure 5.21).

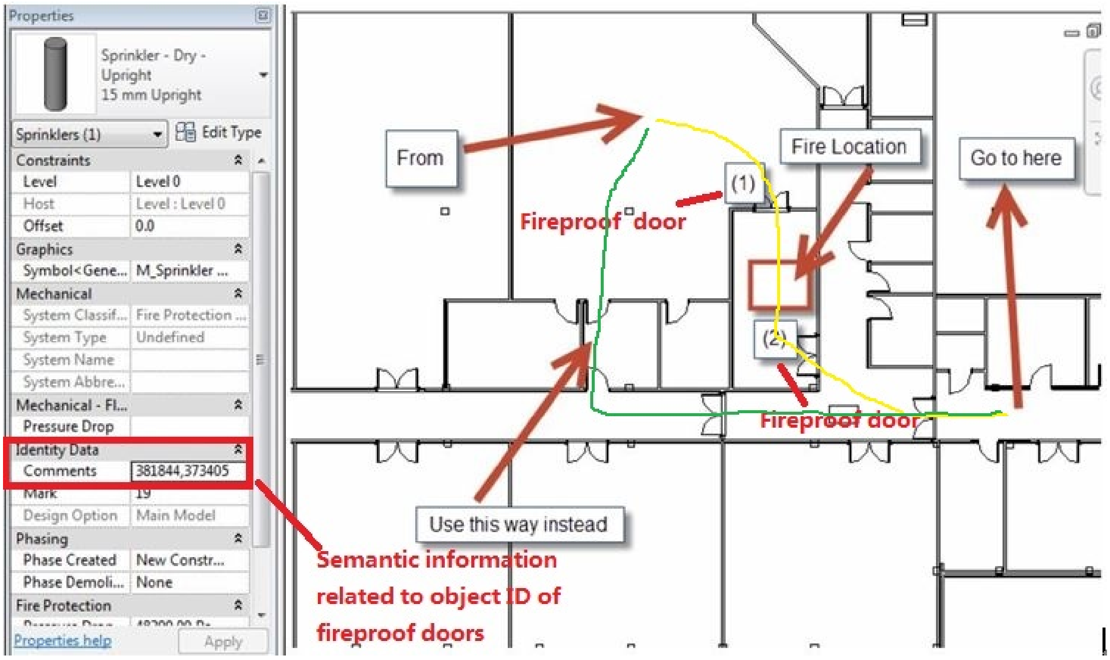
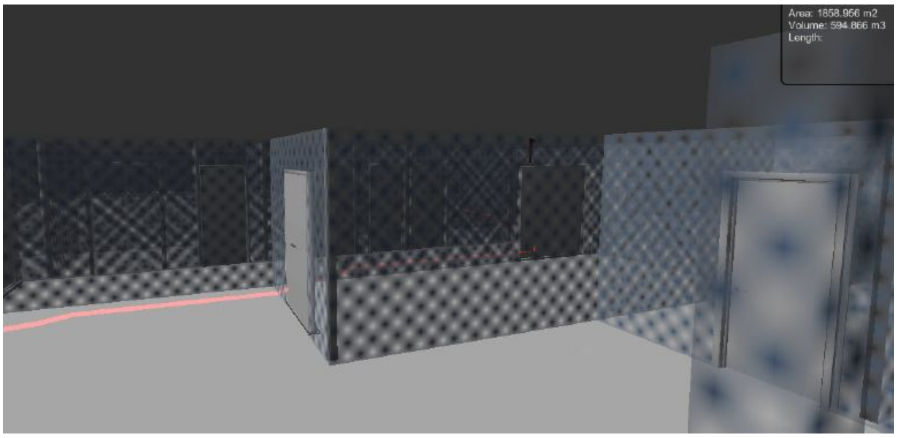
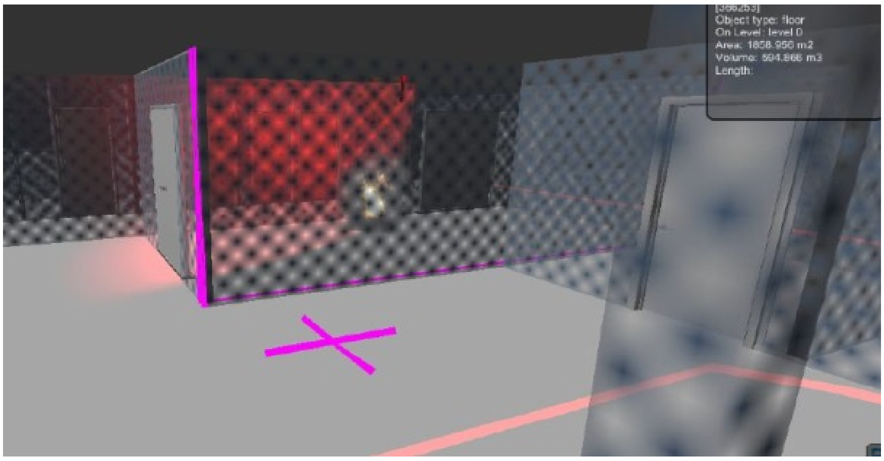


Figure 5.20 The scenario of the fire alarm works with semantic information to automatically change the fire evacuation path ((1) and (2) are fireproof doors which IDs are 381844 and 373405 and referenced to the fire alarm/sprinkler; yellow route is original evacuation path and the green route is the alternative path when fire alarm is activated)



(a) an evacuation path through a safe room



(b) modified evacuation path avoiding fired room

Figure 5.21 The automatic modification of evacuation path in the BIM-VE

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 in the virtual training. The tasks also aim to explore human fire response and performance, which are mainly related to three factors: fire, human personality and the characteristics of the building.

VR devices: 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 get them familiar with 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 by walking around or through the evacuation design from different Unity3D clients (Figure 5.22).

The virtual reality devices such as activate 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 process over 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 Unity3D clients can support many different types of devices and web-browser based interfaces can easily connect large numbers of remote participants 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.

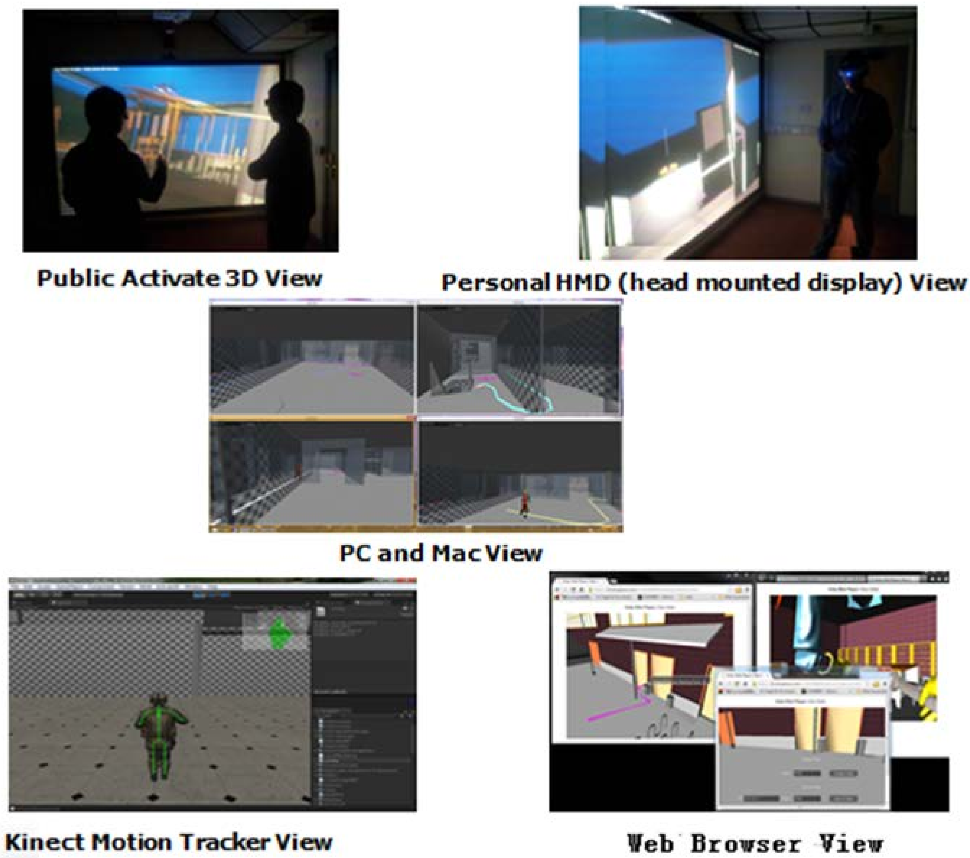


Figure 5.22 The 3D evacuation training on different platforms

5.2.4. Fire evacuation testing

It has been commonly recognized that the unfamiliarity with a new or complicated building will delay the evacuation process. The real west building of Cardiff University's school of Engineering was used to carry out the evacuation testing on mobile devices due to its complex layout (by linking different buildings together historically) and often causes confusion among visitors. Several participants who are familiar or not familiar with the building were chosen.

Firstly, they finished pre-questionnaire and were directed to walk around the engineering school to obtain the basic building information. They were informed of the start location (i.e. the original position to begin the test) and the evacuation assembly point. Then, the participants are guided to the evacuation start point via a route that is different from the evacuation path, and the participants were required to reach the end point without assistance of mobile devices as fast as possible. It was frequently noticed that some of them got lost during the evacuation or chose less efficient route. The results for the participants who were lost or gave up during the evacuation were not included in the experimental results.

Before the second round of testing, the basic functions of the BIM-VE on mobile devices were introduced with 3D virtual space and a corresponding 2D map. 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, the participants were required to evacuate, but with the support of mobile devices running the BIM-VE (Figure 5.23). During the evacuation, the position markers that are set in Revit can help the evacuees to map their positions in the real building with the 2D and 3D virtual environment. After the evacuation testing, the participants were asked to finish a post questionnaire for further investigation.

The BIM-VE has built-in functions to help the general end-users find their location in a virtual world such as 2D map (i.e. the map on the top right corner in Figure 5.23 (a) and (b)) and setting current location as the beginning point (i.e. blue evacuation route in the Figure 5.23 (a) and (b)). Then they can efficiently follow the recommended evacuation path generated by the Unity3D server (i.e. red evacuation route in Figure 5.23 (a) and (b)). According to the post questionnaire results (Figure 5.24), 51% participants thought the function of setting current location as start point helped the participants significantly to locate themselves on the map and follow the recommend path to destination. 22% participants regarded the 2D map was very helpful to them. As a result, 73% participants utilized the BIM-VE designed functions to find the destination efficiently. 27% participants stated they could orient themselves by observing referenced objects in the virtual environment. From pre-questionnaire, it is found that these individuals are mostly engineering students or their families.

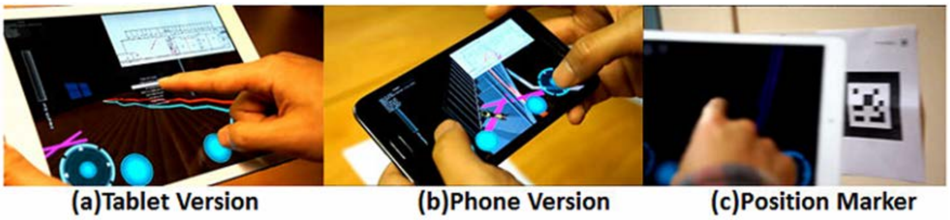


Figure 5.23 Mobile applications for general end-users to carry out effective evacuation

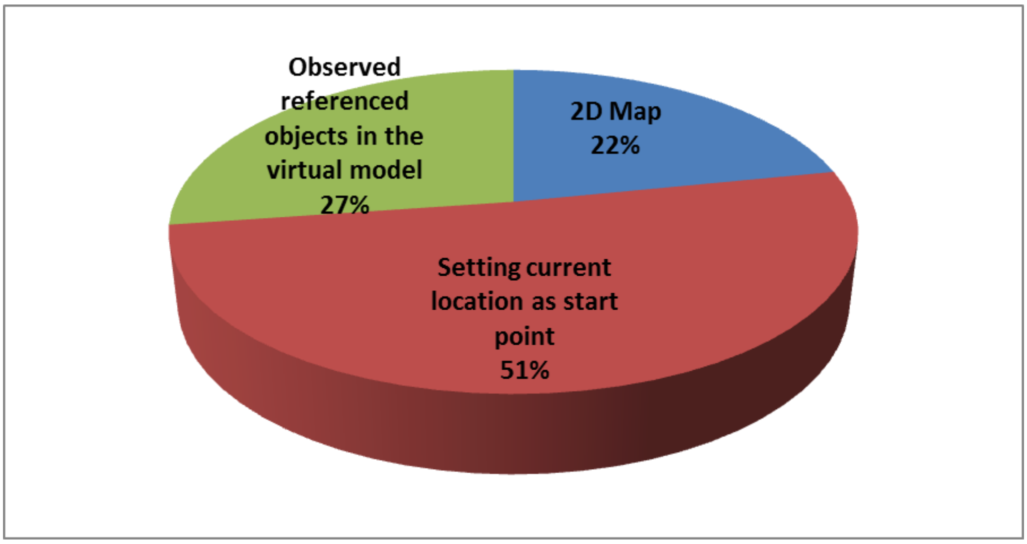


Figure 5.24 Showing the utility of specialized functions to the participants in the virtual world

The BIM-VE also has an important function (i.e. the position marker recognition) to help general end users to locate themselves in the real world. The position markers with their semantic ID were mostly located on corridor junctions or places that might confuse the evacuees. The marker pattern can be recognised at a distance of around 3-4 meters (with the use of iPhone, iPads, and Android phones) in normal lighting conditions and the participants position is computed in under 0.5 seconds (Figure 5.23 (c)). After participants mixing the real and virtual building information, they can efficiently find their destination following the virtual guidance in the real building. The overwhelming portion (95%) of participants found this function was very useful to locate themselves in the real building by synchronizing their locations between the virtual and real world (Figure 5.25). From the pre-questionnaire, individuals who were not sure about whether this function is useful (5%) mostly had little experience in playing computer games. It should be noted that there was no participant thinking this function was unhelpful.

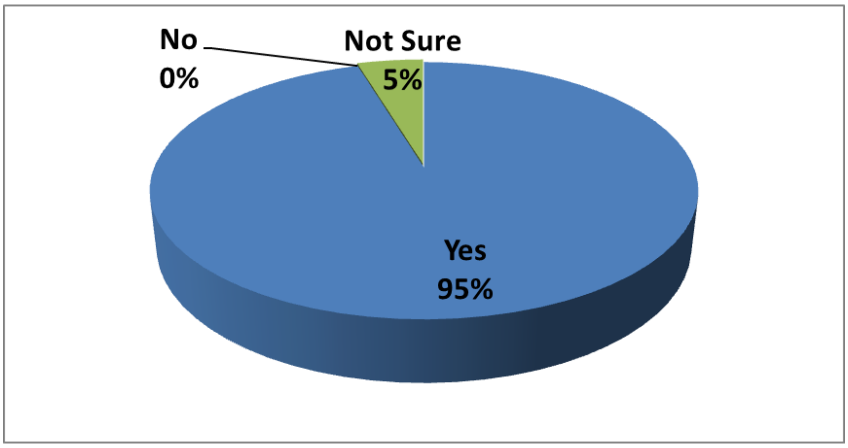


Figure 5.25 Are the location markers useful to find yourself in the real building?

From the records of evacuation testing in Figure 5.26, most participants utilized the mobile interface of BIM-VE to dramatically reduce their evacuation time to the emergency exit (Figure 5.26). the average evacuation time without mobile devices was 8 minutes and 16 seconds while the average evacuation time with assistance from mobile devices was 2 minutes and 30 seconds (Figure 5.27), which provides evidence that the BIM-VE operated on mobile devices can help participants to significantly decrease the time spent to evacuate the building, although its applications during a real emergency situation has to be tested further.

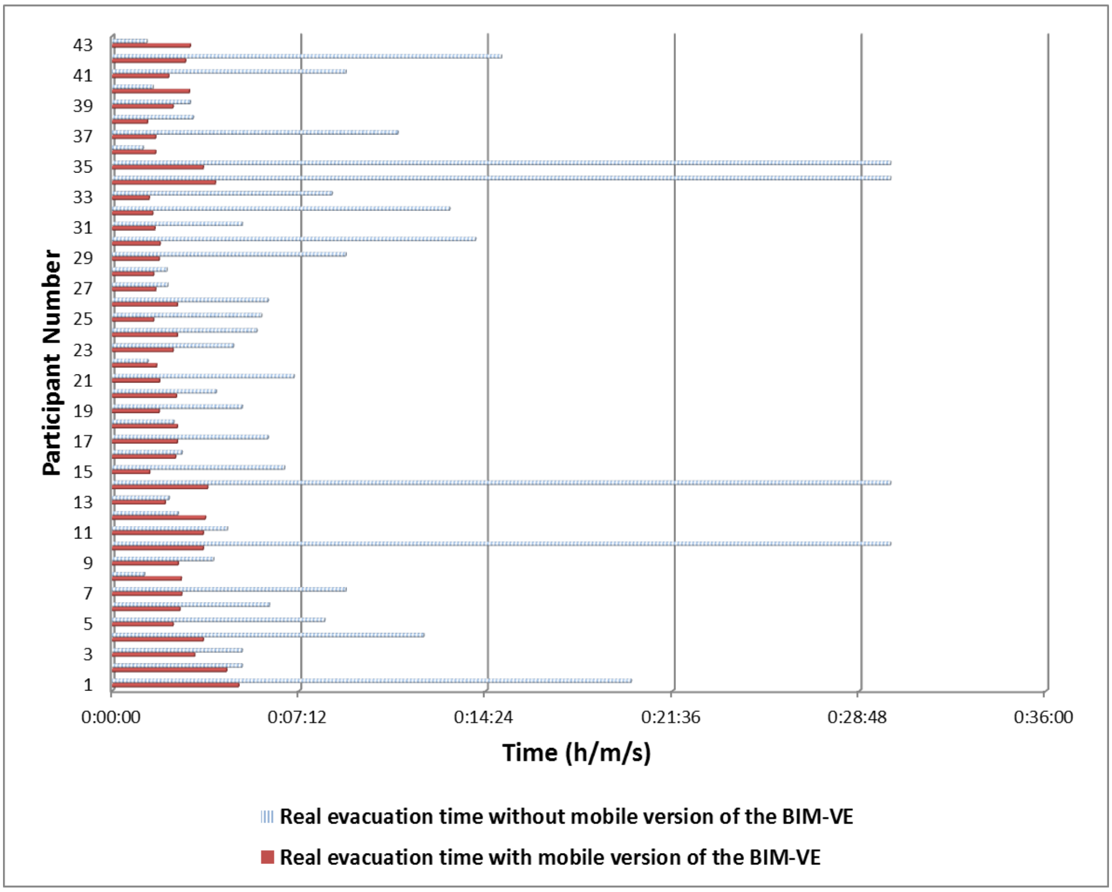


Figure 5.26 Evacuation time of real fire drill with or without mobile devices

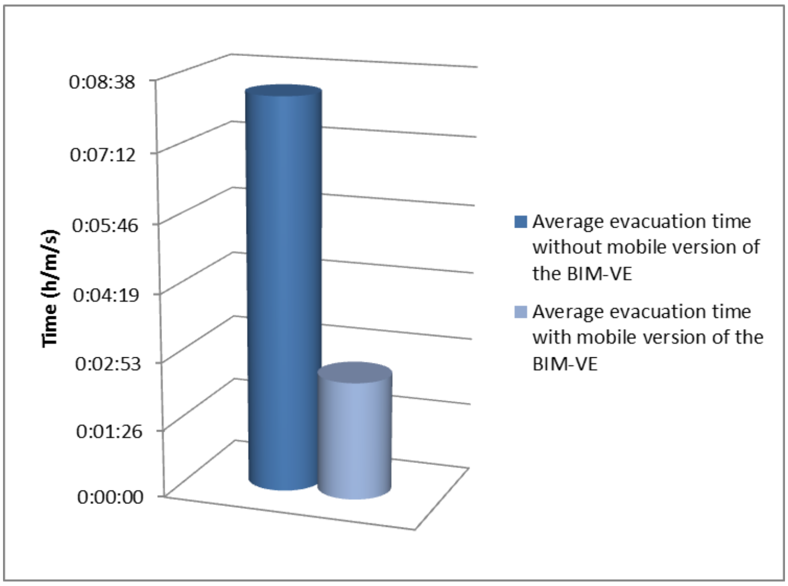


Figure 5.27 Average evacuation time without and with mobile version of the BIM-VE

In addition, running the BIM-VE on mobile devices does not need the extensive installation and maintenance required for other similar systems such as an indoor GPS application (e.g. both tags and readers etc.). The ‘app’ required can easily be downloaded from the Apple store or Google Play store and installed in a smart phone/tablet. It can work via a 3G or 4G signal that is normally not influenced by a fire emergency environment. If mobile cell towers and the BIM-VE server are not physically present in the subject buildings, the end user does not need to worry about damage to locator devices, and gets stable evacuation services if they have a mobile device available. The BIM-VE can work with most smart phones and pads running Android, IOS, Blackberry, and Windows operation system. The participants utilized the BIM-VE on smart pads found it is easy to control due to a bigger screen. This is however not convenient to always carry around. In contrast, those who used the BIM-VE on a smartphone indicated that the screen is too small to easily use different functions, even though this is normally on their person constantly. Therefore, we investigated which mobile device the participant prefers to use in the future (result shown in Figure 5.28). It seems the ‘mobile’ advantage of smart phone (44%) beat the easy-control profit of the smart pad (30%). Some of the participants prefer to use both of them whilst none would not like to use both in the future. The user interface of the BIM-VE in smart phone should be developed to make it more controllable for general end-users.

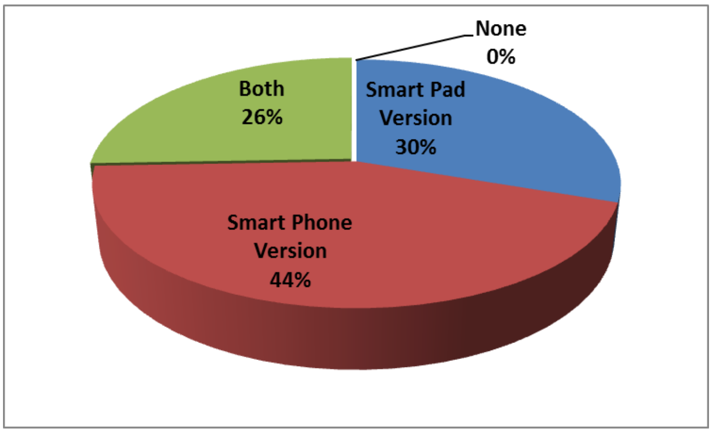


Figure 5.28 Which mobile version the participants would like to use in the future

Finally, the participants marked the mobile interface of BIM-VE support for their evacuation to the destination (Figure 5.29). It is very distinct that most participants though the mobile BIM-VE was very helpful for their evacuation tests although few people chose it was extremely helpful. Those participants who thought the system was not helpful or a little bit helpful were the people who do not usually play game or those who were very familiar with engineering school. Indeed, in the evacuation test, the participants with less gaming experience needed long time to learn how to use the BIM-VE and cannot follow virtual evacuation guides well due to difficulties in handling the system. As for the people who were very familiar with engineering school layout, the BIM-VE might confuse them and delay their arrival at the emergency exit.

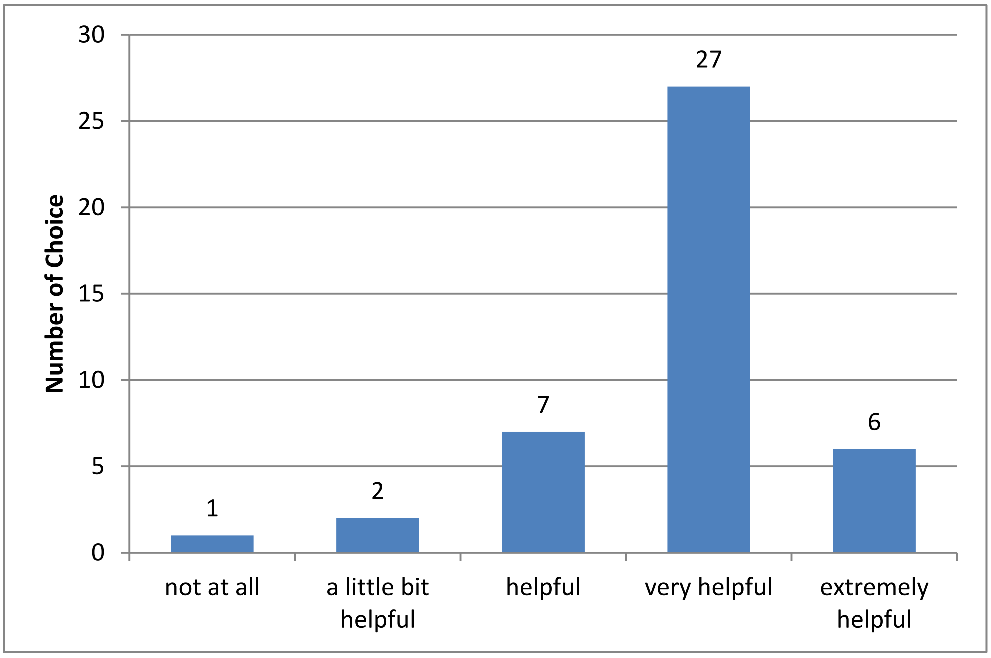


Figure 5.29 To what extent participants agreed the mobile BIM-VE support can help them find evacuation destination

Chapter 6 Experiment Result Analysis

6.1. The analysis method

An important aspect related to development of the BIM-VE for human behaviour research concerns assessment methodologies, particularly it is essential that the results of any virtual experiment can be measurable quantitatively and qualitatively.

A quantitative method is characterised by the assumption that human behaviour can be explained by what may be termed as "social facts", which can be investigated by methodologies that utilise "the deductive logic of the natural sciences"(Horna 1994). Quantitative investigations look for "distinguishing characteristics, elemental properties and empirical boundaries" and tend to measure "how much", or "how often" (Nau 1995).

The experiment based quantitative analysis appropriates to examine the behavioural component of fire evacuation behaviour in both virtual and real experiments. Its advantages to investigate fire evacuation behaviour may be summarised as follows:

- Quantitative methodologies are appropriate to measure overt behaviour during the evacuation.
- They are also strong in measuring descriptive aspects, such as the composition of the fire evacuation behaviour.
- Quantitative methodologies allow comparison and replication.
- Reliability and validity may be determined more objectively than qualitative techniques.
- Providing statistical "proof"

The weaknesses of such quantitative analysis lie mainly in their failure to ascertain deeper underlying meanings and explanations, even when significant, reliable and valid. As noted earlier, psychological factors, such as influence of the threat of danger on evacuees, are important to the investigation of fire evacuation strategy/design. Although quantitative methods can be used to measure such factors, their appropriateness in explaining them in depth is more limited. A further weakness of quantitative approaches lies in their tendencies to take a "snapshot" of a situation, which is to measure variables at a specific moment in time. The behaviours of evacuees may be affected by temporal building environment changes, such as the changes of building layout, or the presence of evacuation leaders, which cannot always be identified within a single quantitative study. The scenarios of virtual experiments are designed based on quantitative methodologies.

Questionnaire based qualitative analyses are those that are associated with interpretative approaches, from the participants' emic point of view, rather than measuring discrete, observable behaviour. This approach complements well the quantitative method used, e.g. the use of questionnaires to provide a deep, rather than broad, set of knowledge about a particular behaviour, and the appropriateness to investigate cognitive and affective aspects of individuals. This depth allows the researcher to achieve empathetic "understanding".

The argument used is that quantitative methods measure human behaviour "from outside", without accessing the meanings that individuals give to their measurable behaviour. If, as many authors have suggested, fire evacuation contains psychological, as well as sociological dimensions, then the emphasis should rather be upon gaining an understanding of how the subjects themselves view their own particular situations. The qualitative analysis allows these understandings to be investigated from the participants’ point of view by questionnaires before and after the virtual experiments. The advantages of such qualitative analysis can be summarised as follows.

- Qualitative analysis allows the cognitive and affective components of evacuation behaviour to be explored in greater depth than quantitative methodologies.
- Qualitative analysis encourages the participant to introduce concepts of importance from the emic aspect, rather than adhering to subject areas that have been pre-determined by the researcher.
- Qualitative approaches permit the identification of longitudinal changes in fire evacuation factors, whereas quantitative approaches tend to take a "snapshot" of behaviour, cognition or affect at the one time the research is conducted.

The main argument against such questionnaire based qualitative analysis might be the concept of validity, in that it is difficult to determine the truthfulness of findings. The relatively low sample numbers often encountered may also lead to claims of findings being unrepresentative of the population. Firstly, the use of around forty participants raises the question whether the views of those participants is truly representative of the general population. Secondly, the choice of case may lead to criticisms of the case being untypical. As will be argued within this paper, the use of a mixed methods approach may enable the researcher to avoid such potential criticisms after setting the specific scenario.

The crucial aspect in justifying a mixed experimental analysis is that both single methodology approaches (qualitative only and quantitative only) have strengths and weaknesses. The combination of analysis, on the other hand, can focus on their relevant strengths. The researcher should aim to achieve the situation where "blending qualitative and quantitative methods of research can produce a final product which can highlight the significant contributions of both"(Nau 1995), where "qualitative data can support and explicate the meaning of quantitative research" (Hammersley 1993). By adopting the following assumptions, the mixture of quantitative and qualitative analysis should ensure that the final results maximises the strengths of each.

- Questionnaire based qualitative analysis allows the researcher to develop an overall "picture" of participants as well as their possible fire evacuation behaviour under investigation. This may guide the initial phases of the research before and after experiments (e.g. pre-questionnaire and post-questionnaires).
- The descriptive analysis, such as the individual information of the participants before the experiments, may allow a representative sample to be drawn for the qualitative analysis after the experiments (by post-questionnaires). Marsh, et al. who notes that quantitative research (experiments) may confirm or deny the representativeness of a sample group for such qualitative research. Thus the mixed methodology will guide the researcher who is carrying out qualitative research, that his or her sample has some representativeness of the overall population (Moscovici

1982).

- Human fire evacuation involves cognitive and affective characteristics, which are hardly investigated by experiments. Thus a qualitative analysis after the experiments is appropriate to investigate these aspects from the point of view of the participants.
- Many fire evacuation researches are still largely exploratory. The use of questionnaire based qualitative analysis allows for unexpected developments that may arise as part of such research (i.e. serendipity).
- Quantitative analysis may complement the findings of qualitative methods by indicating their extent within the population of participants.
- Quantitative analysis may confirm or disconfirm any apparently significant data that emerge from the experiments. Thus, for example, if level of game experience of participants appears to have an effect upon aspects of evacuation behaviour in the virtual environment, quantitative methods can be used to enable statistical testing of the strength of such a relationship.
- If such a relationship is determined, then quantitative methods are weaker in providing explanation. Post-questionnaire-based qualitative analysis may assist the researcher in understanding the underlying explanations of significance.

As noted before, the purpose of this research is not to suggest that a mixed methodology is the only suitable research design for this topic, rather that it is an appropriate, and at times desirable design. The overall choice needs, of course, to be the most suitable one to achieve the objectives of the research. A mixed methodology, however, has a number of advantages within fire evacuation behaviour research, as well as other social science disciplines, and may be able to enhance the quality of such work in such ways as have been outlined.

6.2. Scenario based human emergency behaviour analysis

In terms of human emergency behaviour research, the Unity3D server has an easy-to-use graphical user interface (GUI) connected to the design library under the control of the experiment administrator. After the virtual environment built by the BIM-VE, the general participants can use different client interfaces to connect the server to begin the virtual drills while the administrator can distribute key factors influencing the fire emergency evacuation (Appendix C- Experiment Results for Human Behaviour and Evacuation).

Individuals took part in the human emergency behaviour investigations (including just the questionnaire or virtual fire drills parts or both of them). This Section will first demonstrate the results of the experiment from recordings and post-questionnaires to find any trends and conclusions. Then the pre-questionnaire information will be examined to establish clear correlations between results and participant characteristics. Finally the participant feedback and general observations made will be investigated to draw on further information before a detailed discussion. The average response has been taken for the analysis in the following examples.

6.2.1. Observation

Specifically, 11 people did not take part in the virtual fire drills because of various reasons. One participant partly finished the virtual fire drill and chosen to quit the experiment because of screen vertigo. Therefore, thirty-three participants utilised first person view desktop version of the BIM-VE with the 3D screen to finish the virtual fire drills. Figure 6.1 shows the number of participants who perceived and estimated dangers before fire evacuations comparing those who did not in the virtual drills. It can be observed that most participants in the virtual drills hesitated to begin the evacuation because they tried to identify the dangers/hazards and their level of significance beforehand. The participants who have adopted this type of behaviour more than once are shown in Figure 6.1, with a comparison to those who did not.

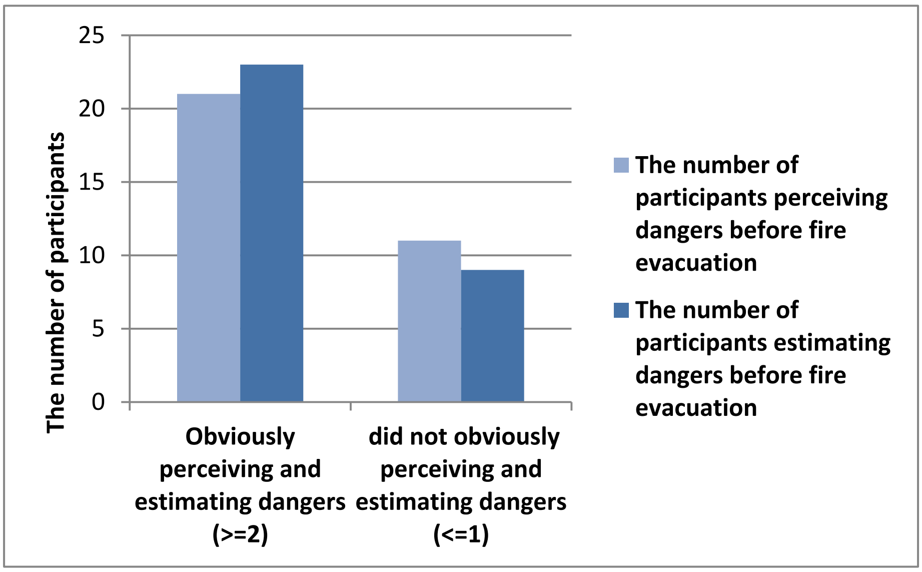


Figure 6.1 The investigation of people who perceived and estimated the threat of danger in the virtual fire drill

To validate this trend, the post-questionnaire also asked the participants whether they estimated the dangers in the experiments and whether this influenced their evacuation behaviour, results which are shown in Figure 6.2.

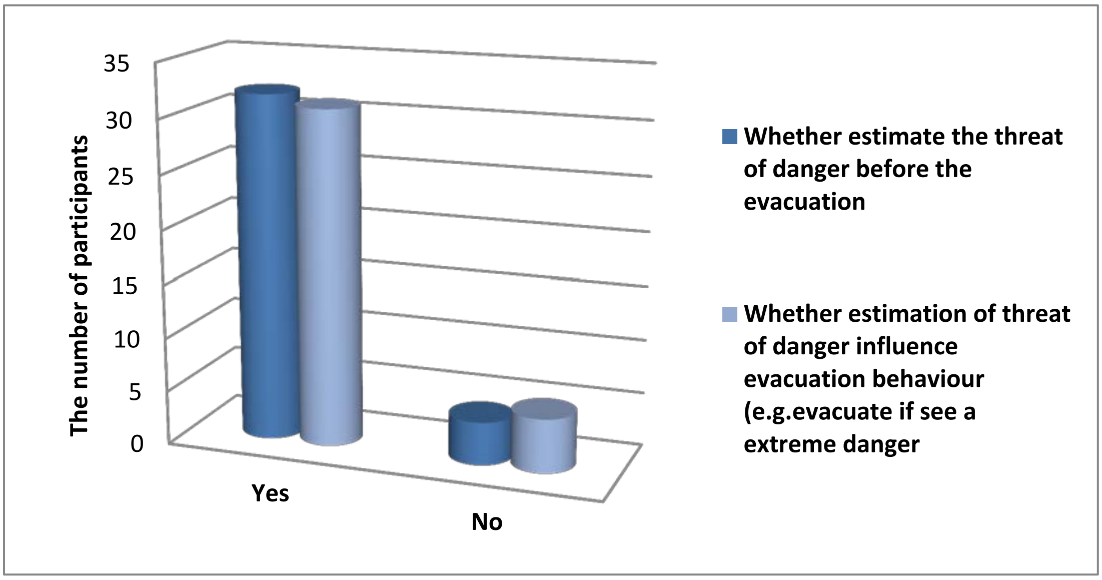


Figure 6.2 The influence of estimation of threat of danger on fire evacuation behaviour

Most participants estimated the threat of danger before they began to evacuate, and this has apparently influenced their evacuation behaviour. This might because some observations in the virtual fire drill are merged with the ‘No’ group. According to the pre-questionnaire, those people who did not perceive and estimate the dangers are mostly Cardiff engineering school students or the people who are familiar with layout of west building of the Cardiff engineering school.

Moreover, the post-questionnaire explored whether facing uncertainty about the danger of the situation and confronting complicated fire environment (processing too much in formation) increased the participants' stress and delay their evacuation, results which are shown in Figure 6.3. The participants who chose 'Yes' have an overwhelming tendency. It has also been observed that the participants who controlled the avatar in the virtual drills became overwhelmed when the experiment assistant introduced too many emergency objects around them or the participants which did not know the engineering school building at all.

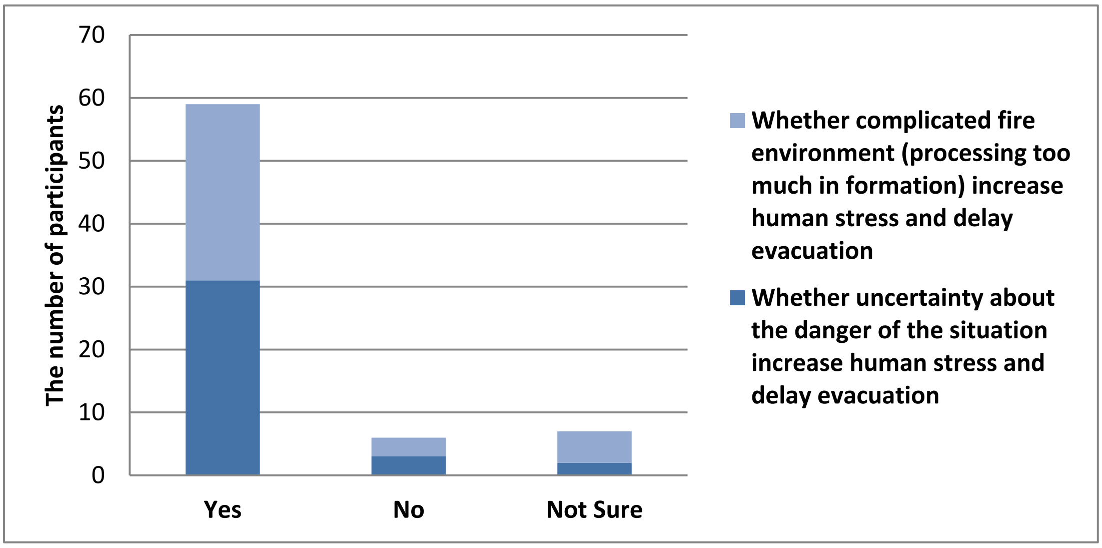


Figure 6.3 The influence of emergency environment on human fire evacuation

What perception of factors made the participants begin to evacuate in the virtual fire drills is also investigated by the post-questionnaire (Figure 6.4), because it is hard to judge them through the recordings of virtual experiments. It is observed that the spoken message alarm (11%) is easier to be noticed and make the evacuation begin than the slow whooping alarm (7%) although both of them only occupy small portion (18% in total) of the pie chart that investigate the perception factors that made people begin to evacuate. However, participants in the virtual drills seldom began to evacuate after hearing alarms, rather preferring to wait until they were compelled by virtual dangerous factors. This is also because they were told to begin to evacuate when they felt they are in danger. It should be noticed that alarm lightings (23%) are more noticeable than the alarm sounds. From Figure 6.4, it can be observed that the alarm light have the same degree of influencing the participant to evacuate as fire and smoke/toxic gas. There is slight difference between these three factors (2% each), which is generally due to its visual component. Therefore, visual factors can influence more people to begin to evacuate than the audio factors; this is also dependant of the evacuee's assessment of the danger.

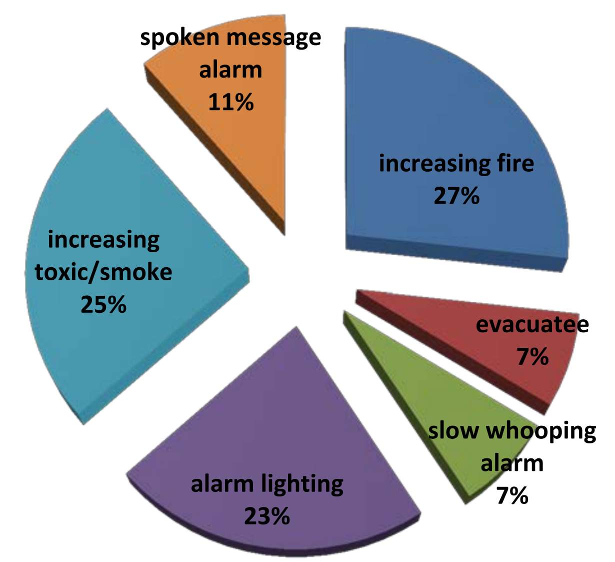


Figure 6.4 What perception factors made people to begin to evacuate

6.2.2. Collaboration and group preferring

The previous paper utilised questionnaires and direction Q&A methods to reveal that most people have a trend to wait for other people to respond to the emergency situation, communicate and collaborate with others, and become a follower during the evacuation. The BIM-VE generated the dynamic virtual emergency environment to test whether the former investigations are correct. Figure 6.5 shows the investigation results about whether the participants wait for others to respond first by both virtual experiments and post-questionnaires. It can be seen that the participant who did not wait for the other people to respond first (i.e. 'No') account for more than half regardless of the results from virtual experiments and post-questionnaires, which is different from the result of previous research. This trend is clearer in the virtual fire drills than in the post-questionnaire because those people who chose 'Not Sure' in the post-questionnaire had to perform their evacuation behaviour within the virtual drill (Figure 6.6). Moreover, Figure 6.6 also illustrates the consistency and accuracy of virtual experiment results compared to the results of the post questionnaire. Apart from the participants 2 and 3 which did not attend the virtual experiments, 7 of 33 total participants had different responses in the virtual drill and post-questionnaire. Among these people, 8 participants chose 'Not Sure' in questionnaire, but performed specific responses within the virtual drills whilst only 1 person did not respond clearly in the virtual drills.

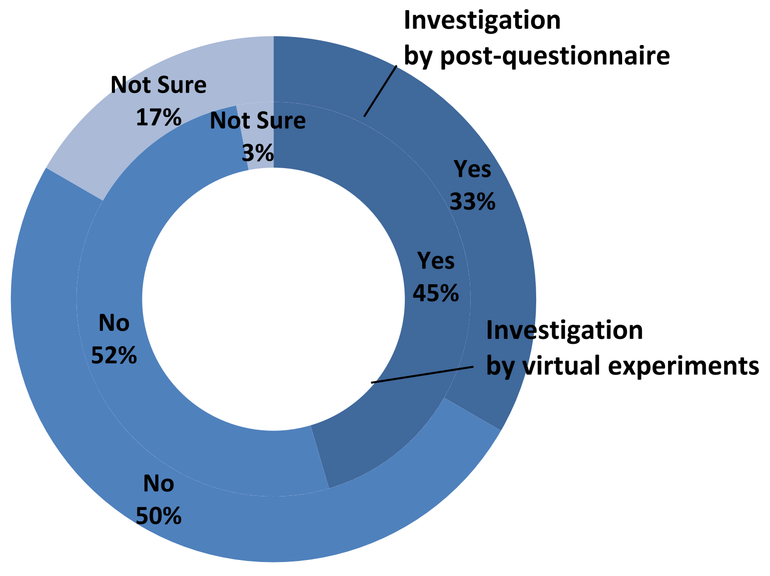


Figure 6.5 Chart of people waiting for other people to evacuate first

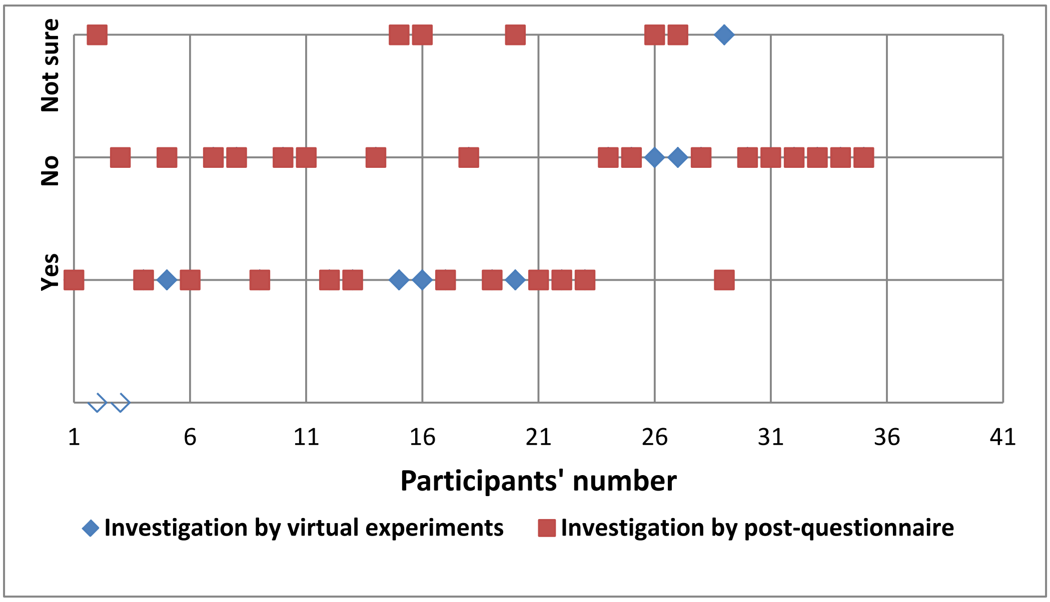


Figure 6.6 Comparisons of whether waiting for other people to respond first by virtual experiments and post-questionnaires

Similarly, whether people adopt the role of a follower during the evacuation can be investigated by both virtual experiments and post-questionnaires, results which are shown in Figure 6.7. The amount of times when participants followed other virtual evacuees when meeting them was recorded during the virtual drills. Those participants whose following times are higher were recognised as a follower, and vice versa. The results from the post questionnaire show that most participants preferred to pay the role of follower during an evacuation, but virtual experiment contradict this. The reason that caused these conflicted results might be because the participants behaved differently by instinct when facing dangers and got disoriented in the virtual fire drills.

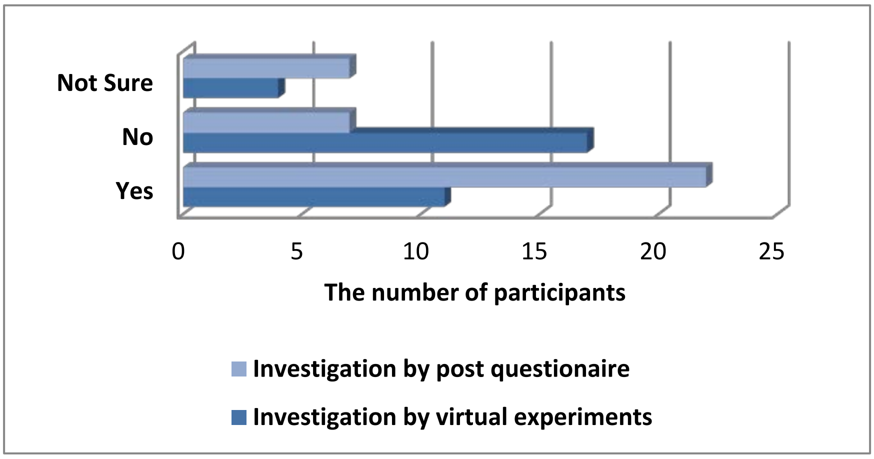


Figure 6.7 Investigation of whether adopt the role of a follower during fire evacuation

Figure 6.8 shows the possibility percentage of each participant becoming a follower when they meet other evacuees, which was calculated by their performances in the virtual fire drill. Beside participants 2, 3 and 14 who did not attend this virtual drill, participants with 0% possibility percentage of following are all from the engineering school or familiar with engineering school layouts according to background information of the pre-questionnaire. These results can be utilised for future development of evacuation artificial intelligence to improve building emergency design.

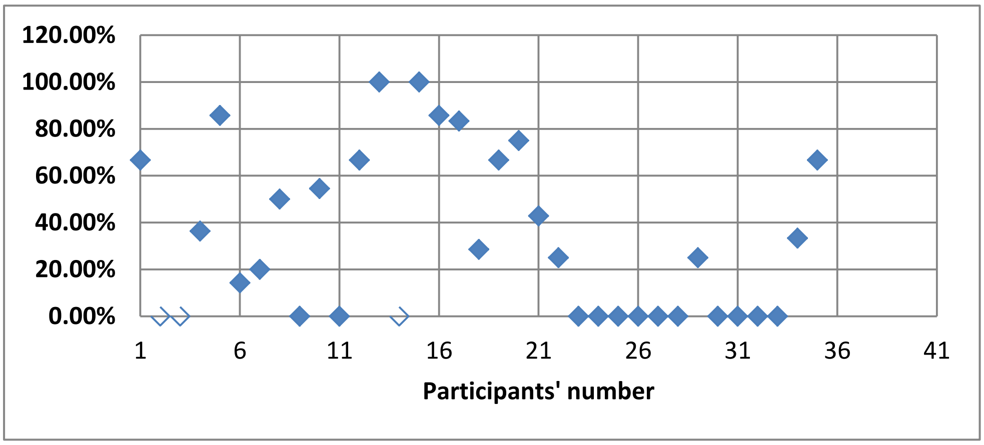


Figure 6.8 The percentage of those adopting the role of a follower

The average percentage of participants becoming an evacuation follower is calculated and expressed in Figure 6.9. It is observed that people were more inclined to become a follower (to carry out group evacuation) (39%) than to continue their individual evacuation (61%) when they crossed other evacuees. And this result does not correspond to previous findings of other researchers (Shields and Boyce 2000; Xudong et al. 2009). However, the post questionnaire investigated what is the participants' preferred role when they begin to evacuate, showing that the most people were willing to follow others rather than leading (Figure 6.10). Through the open questions, it was found that this is due to the fact that most people were not familiar with the complicated layout of the engineering school building (even if they are engineering school students) or that were worried they did not have enough confidence to call for help to escape.

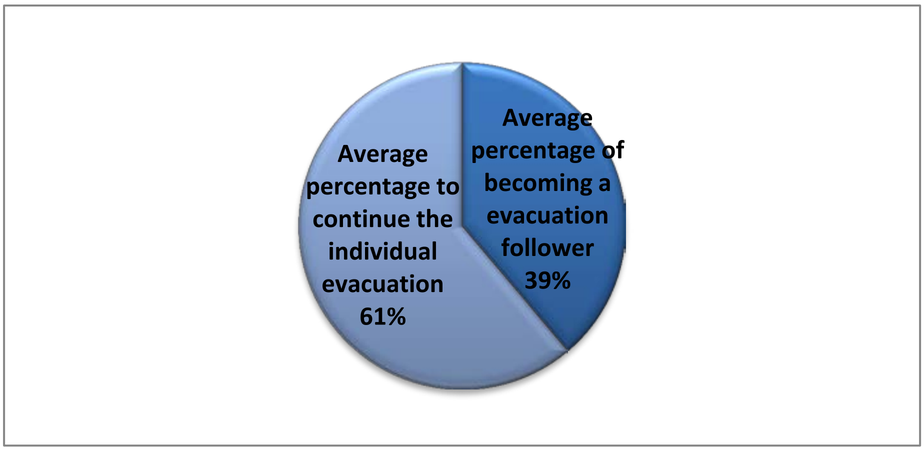


Figure 6.9 Average percentage of evacuation followers in virtual experiments

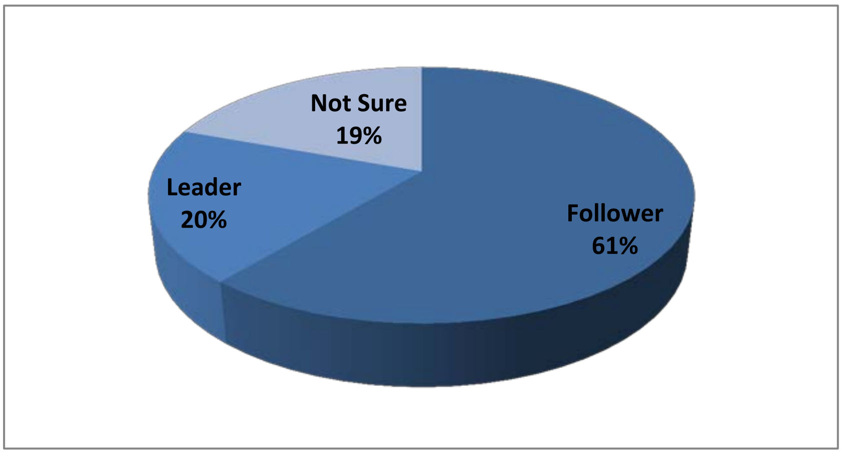


Figure 6.10 Investigation of what is participants' preferred role during the evacuation by post questionnaire

Because the avatar controlled by participants was spawned in different places and the virtual environment was changing, not all participants faced the certain situation to prove the previous research in the virtual fire drills. Figure 6.11 shows whether the participant tried to communicate and collaborate with other virtual characters. Before the evacuation, 16 of the participants crossed another virtual character, 10 of which approached the virtual characters to communicate; during the evacuation, 11 of 17 participants tried to communicate and collaborate with the other virtual evacuees in the virtual fire drills. The results from the virtual experiment proved that most people tend to communicate with others regardless if before or during the evacuation.

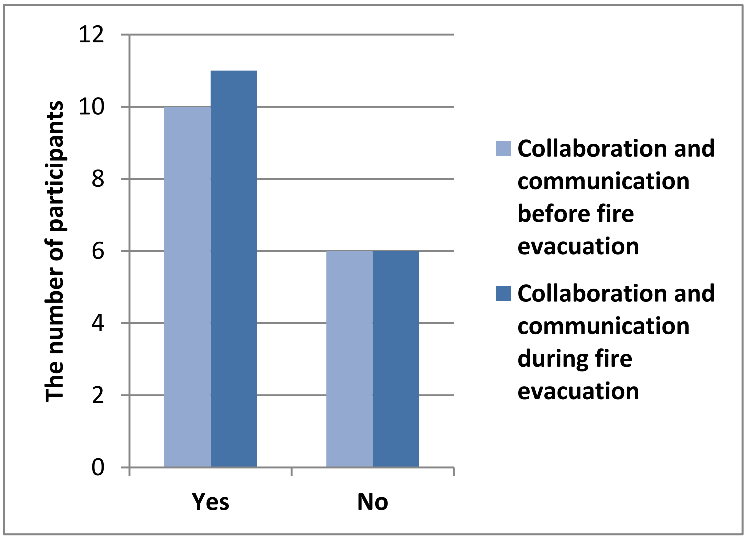


Figure 6.11 Collaboration and communication before and after the evacuation

In the post questionnaire, the collaboration and communication preference of participants was double validated and more apparent, which is shown in the Figure 6.12. Furthermore, the post questionnaire investigated the influence of social bonds on human fire evacuation behaviour. Specifically, it explored whether the family members or friends would try to respond to emergency situation as a group (Figure 6.13). 93% of the participant responded to the emergency with their friends or family members, which proved that the social bond might influence the fire evacuation considerably.

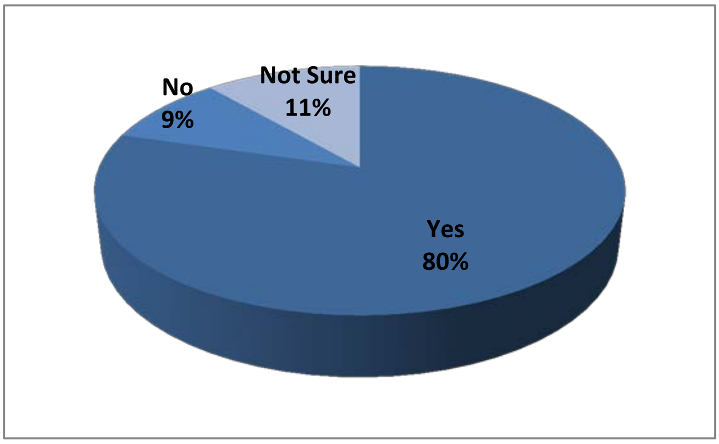


Figure 6.12 Investigation of whether evacuees are inclined to collaborate and communicate with others according to post questionnaire

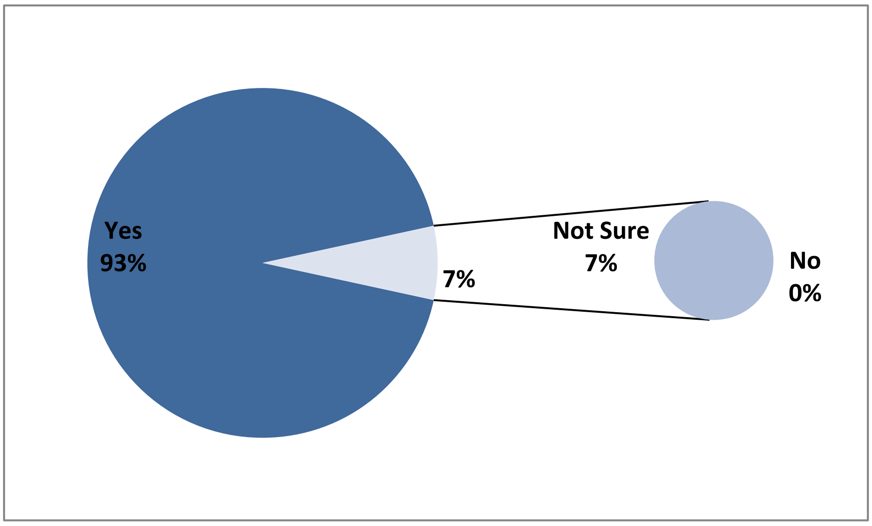


Figure 6.13 The investigation of whether family members and friends try to respond to the emergency as a group

The participants had a preference to collaborate and evacuate with others especially those who are acquainted. However, the density of evacuates often influenced evacuation efficiency in the virtual fire drills. It was observed that the participants were often stuck by other virtual characters and killed by the extreme dangers. This is especially the case in narrow areas such as small evacuation exits and stairs. Therefore, it can be concluded that the high evacuee density means a high probability of fatalities in the narrow area in the event of fire.

6.2.3. Role and physical position

As discussed, few participants preferred to carry the group evacuation as followers rather than the evacuation leader. However, whether the presence of leader possessed a positive effect on evacuation is a subject of further investigation. From the virtual fire drills, it was often observed that some participants followed others into extreme fire dangers such as thick smoke or large fires, and often be terminated by doing so. The rate of success of a group depended highly on the leader's decisions. The results of the Q&A shows the reason why participants followed others virtual evacuees is being unfamiliar to the building. This reason can be further illustrated psychologically from the post-questionnaire.

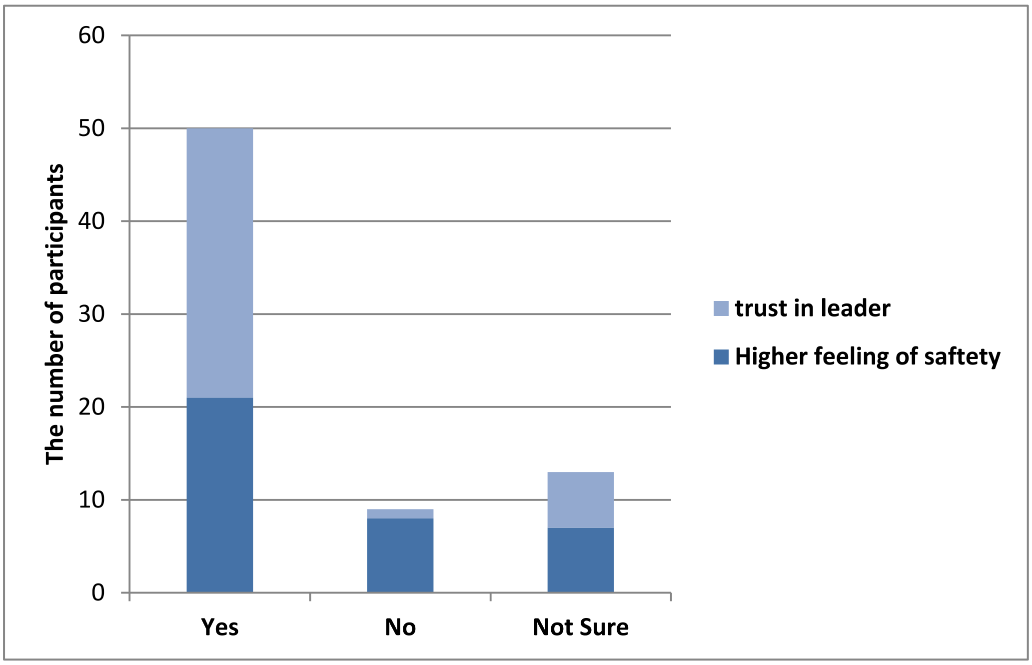


Figure 6.14 The reason why the participants prefer to follow the leader

It can clearly be seen from Figure 6.14 that the number of participants who trusted in the evacuation leader felt safer is significantly higher than the rest. From the post questionnaire, the presence of evacuation leader posed positive effect on fire evacuation (80%) and increased the sense of safety (58%). See Figure 6.15. From direct Q&A, the reason why those people who trusted the leader but still felt unsecure is because they did not know the leader well enough and had doubts of the leader's ability. The post questionnaire also revealed that 100% participants thought a well-educated and well-trained evacuation leader or team can improve the speed of escape and the use of emergency exits.

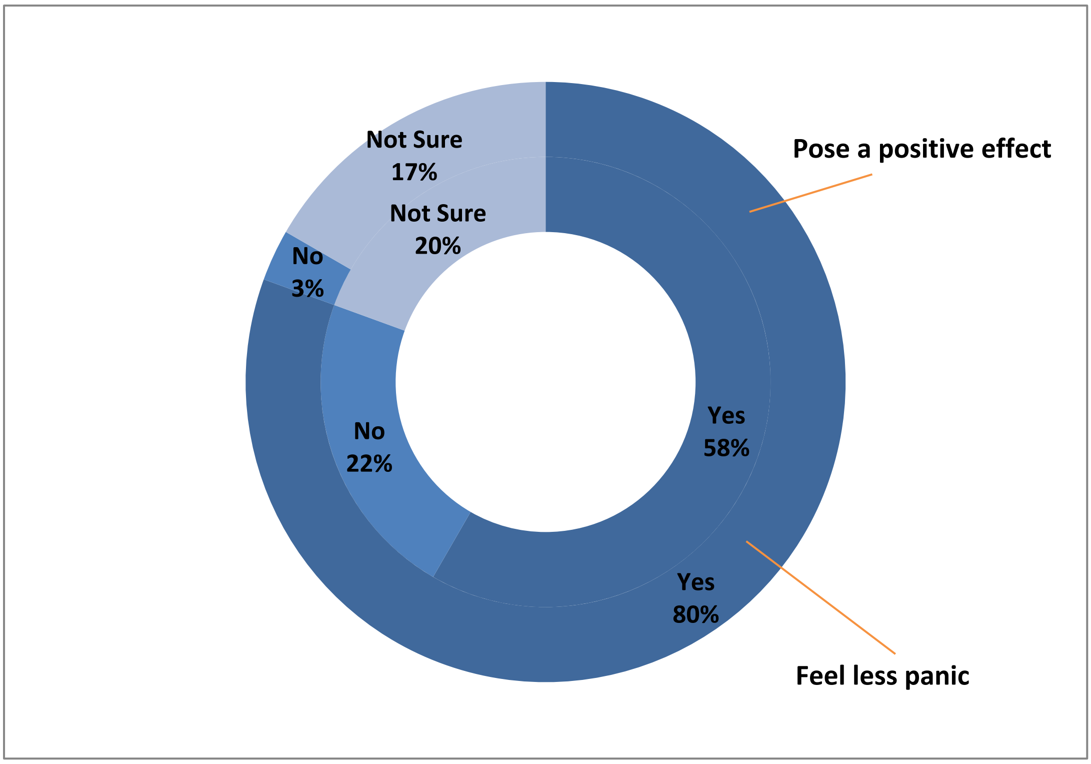


Figure 6.15 The result of effect of presence of leader on evacuation by post questionnaire

Due to the current limitation of scenarios generated by the BIM-VE, some factors influencing fire evacuation cannot be fully investigated by virtual experiments. Therefore, the post questionnaire would play a key role to research these factors. Although there are no specific scenarios generated to test these factors, the virtual fire drills can help the participants immerse into a fire evacuation, which can enhance the accuracy of subsequent post questionnaire results to some extent. For example, Lawson G indicated that people who are standing or walking are more likely to leave the room than people who are present in a prone or sitting position (Lawson 2011). Figure 6.16 shows that 78% of the participants agreeing to this.

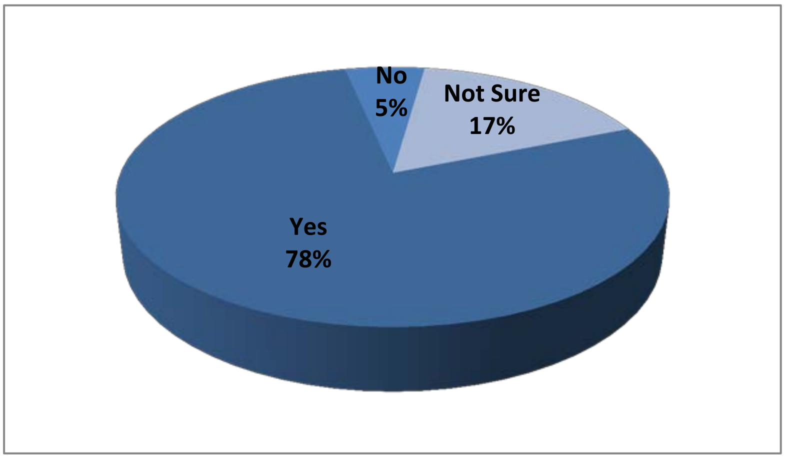


Figure 6.16 Investigation of whether people who are standing or walking are more likely to evacuate according to post questionnaire

However, the previous research conclusion cannot always be proved to be correct by post-questionnaires following virtual experiments. For instance, it is proposed by some papers that people are prior to finish their jobs before their evacuation if they are not sure the danger of the situation or have duties (Lawson 2011). Nevertheless, Figure 6.17 demonstrates the results in contradiction to the previous research conclusion. Specifically, 42% participants chose to evacuate without caring about the duties while 36% participants chose to finish what they were doing first. The result is contrary to the traditional conclusion although it is should be further validated by developing specific scenarios of the BIM-VE. The BIM-VE should create a suitable scenario to make the results more accurate by making the 22% people who were not sure about what they should do to clearly perform in the virtual drills.

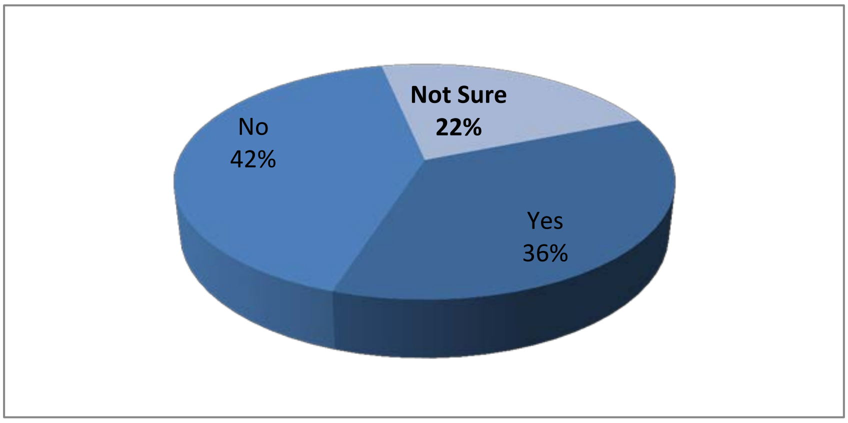


Figure 6.17 Investigation of evacuees who are not sure of the danger or have tasks

neglecting the alarms according to the post questionnaire

6.2.4. Degree of familiarity with building layout

It is common recognised that the evacuees usually use familiar routes (normally the main exit or the entrance of building) to get out of the building, depending upon the affinity of the path towards them. The research results were based on real drills and questionnaires. However, the conclusions have not been validated by repeating virtual fire drills although they are cheap to simulate. Figure 6.18 shows that the number of people who chose the evacuation path based on familiarity and affinity are significantly higher than those who were not based upon them. Participants often utilised the main entrance to get out of the building, especially, engineering students. Some of them chose the rarely used stairs to get out of the building, something which never occurred to participants from the business school unless they were being lead there. It was also found that some engineering students searched for the water for firefighting in the toilet and water room. Irrespective of their background, students often took the same path in the future depths, sometimes trying to ignore the previously encountered dangers. This trend is marked as 'Partly Yes' in Figure 6.18 because the participants used the temporarily familiar route to evacuate. Only one participant randomly chose the evacuation route without observable rules.

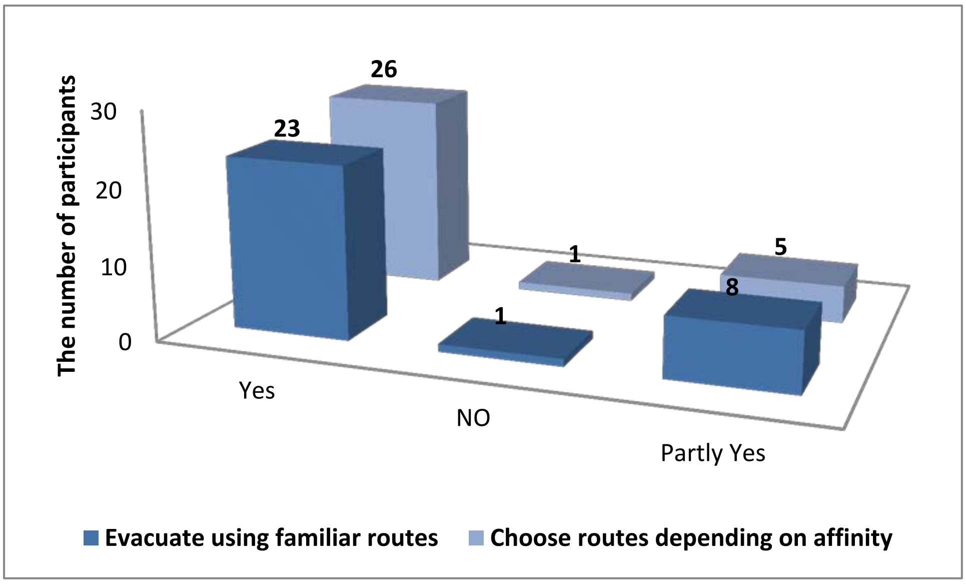


Figure 6.18 Investigation of evacuation route preference by virtual experiments

It should be noticed from Figure 6.19 that the participants referenced the level of their familiarity and affinity with the building layout at the same time (i.e. overlapping red dot) to choose the evacuation route. Only three participants repeated the evacuation routes that are just recognised during the evacuation. These individuals in questions are all unfamiliar with the building.

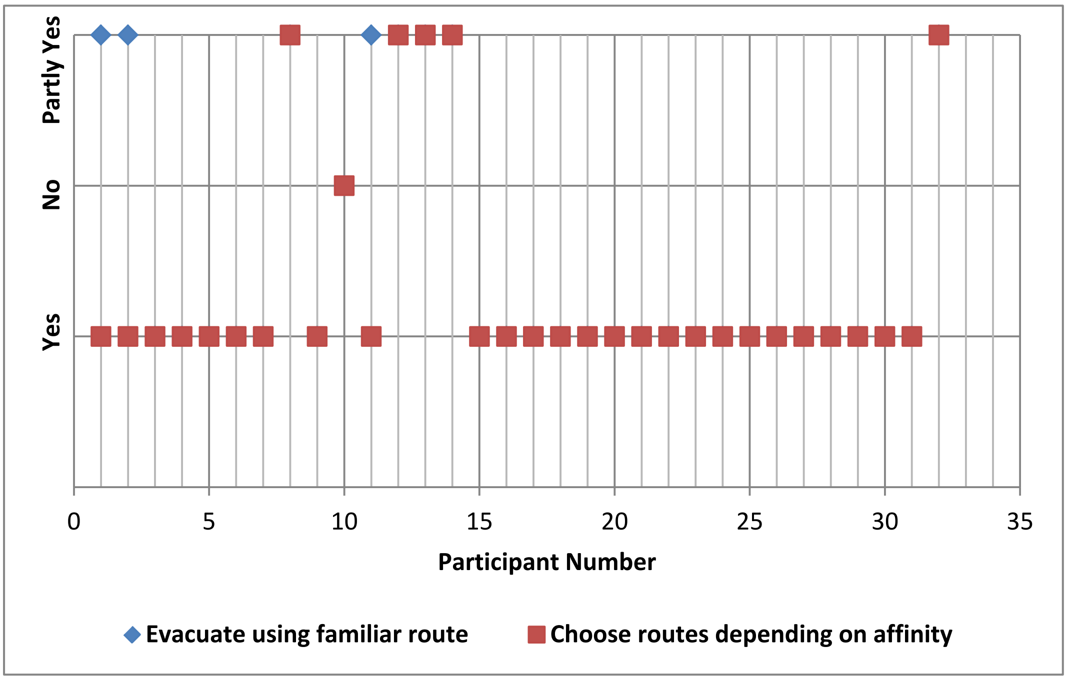


Figure 6.19 Investigation of how to choose evacuation path depending on familiarity

To supplement the observation results of the virtual experiments, the post questionnaire was utilised to investigate whether the participants used the main exit/entrance (Figure 6.20). It can be seen that 84% of participants chose the main exit/entrance to evacuate, which is considerably from the rest.

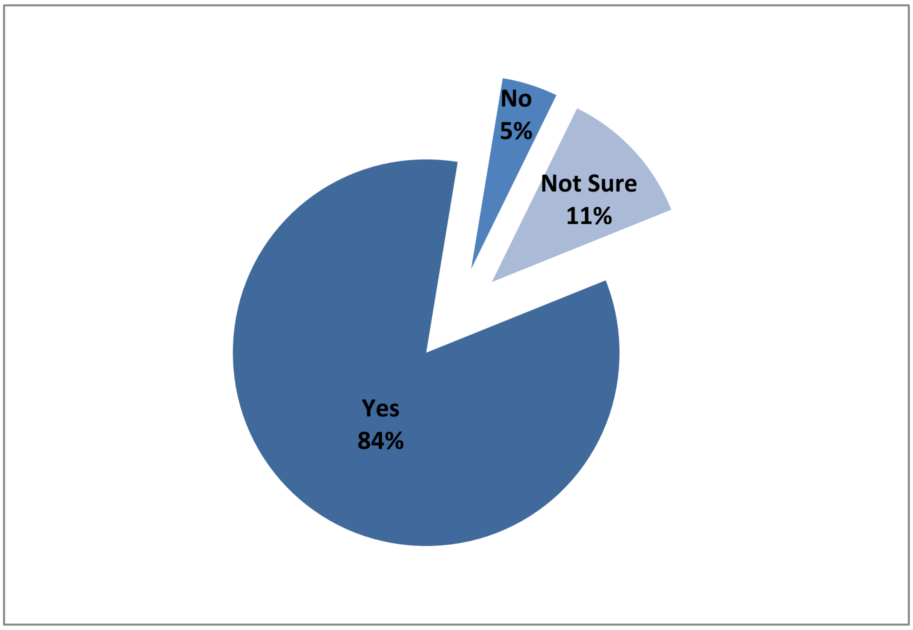


Figure 6.20 Percentages of whether evacuees using the main exit/entrance of the building (post questionnaire)

The building layout played a pivotal role in choice of evacuation path regardless of the evacuee's familiarity with the building. It was discussed that the maximum flow rate capacity of exits depends on effective exit rather than actual exit width. Therefore, the BIM-VE generated the dynamic scenarios that include wide doors with random evacuees passing through and narrow doors with or without evacuees to investigate this (Figure 6.21). 62% participants were observed to have slowed down when they passed through wide doors with evacuees passing randomly. In contrast, the participants normally followed the ordered evacuees to pass the narrow doors without obvious speed decrease. Figure 6.22 shows that most participants took part in more than one scenario and faced such situation several times. It can be seen that moving speeds were negatively influenced by irregular running evacuees even when passing through wide doors.

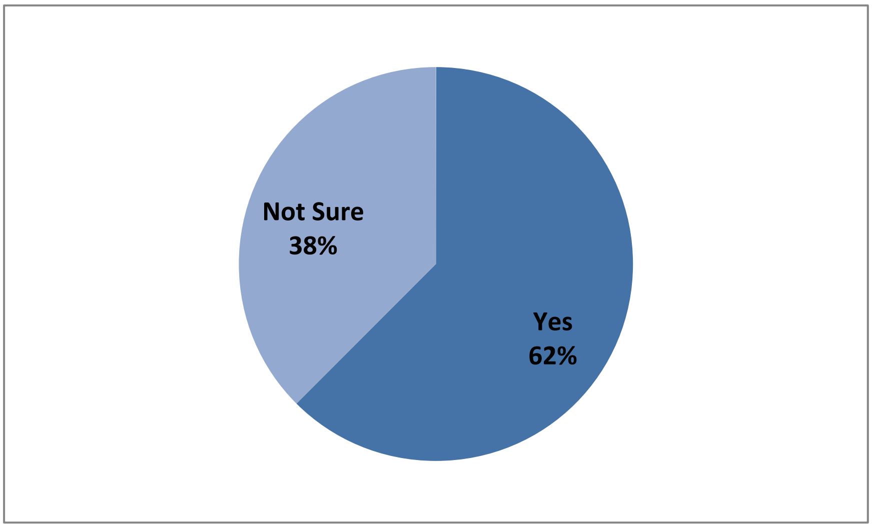


Figure 6.21 Is maximum evacuation flow is based on effective evacuation or just the width of exit doors? (Virtual experiments)

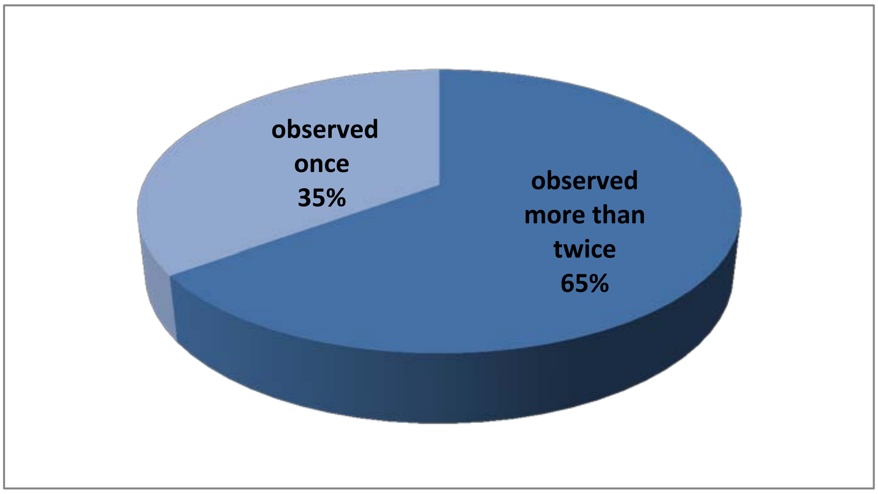


Figure 6.22 The times of observation of participants' running speed is slowed down (virtual experiment)

According to previous researches, open doors are more likely to be used as fire exits. This is also the case observed through the scenarios generated by the BIM-VE. The BIM-VE randomly moved some exit doors and created open space to test human behaviour (refer to Figure 6.23). 78% were inclined to use the opened fire exits/ space. Although there were several people which randomly chose the evacuation exit (22%), some of them were observed to choose the open exit/space to get out of extreme dangerous environment by instinct (6% marked as ‘Partly Yes’).

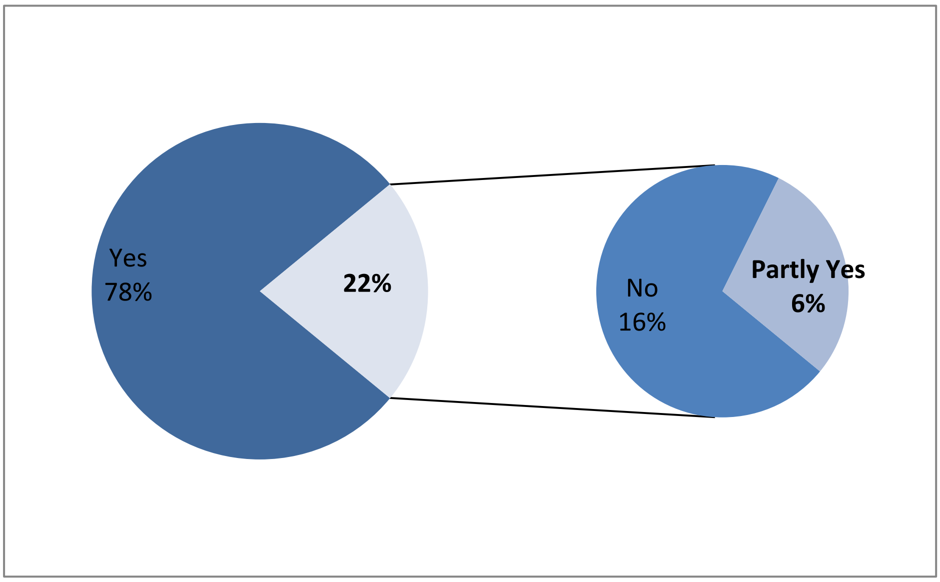


Figure 6.23 Are the open fire exists frequently used?

Evacuees often use the fire exit with easy accessibility and tend to choose fire safe evacuation routes. Results show there is no obvious preference for evacuees to judge the accessibility of fire exit (Figure 6.24). The number of evacuees who chose the evacuation route without considering the accessibility of exit (53%) is a little bit higher than those who cared about accessibility (47%). Within the group who care about the accessibility of the fire exit, it can be observed that they often chose long cleared corridors to get to those less dangerous exits. Specifically, they prefer to choose cleared long corridor rather than short cut way with dangers and objects. If there are dangers near an exit, they normally chose the other exits without dangers to get out of the building. The emergency exit surrounded by dangers was only chosen when there was no alternative. According to pre-questionnaire, the participants who did not care about accessibility of fire exit mostly were engineering school students or the individuals who knew the building layout because they used their knowledge to identify where to go, they cared less about the hazards nearby.

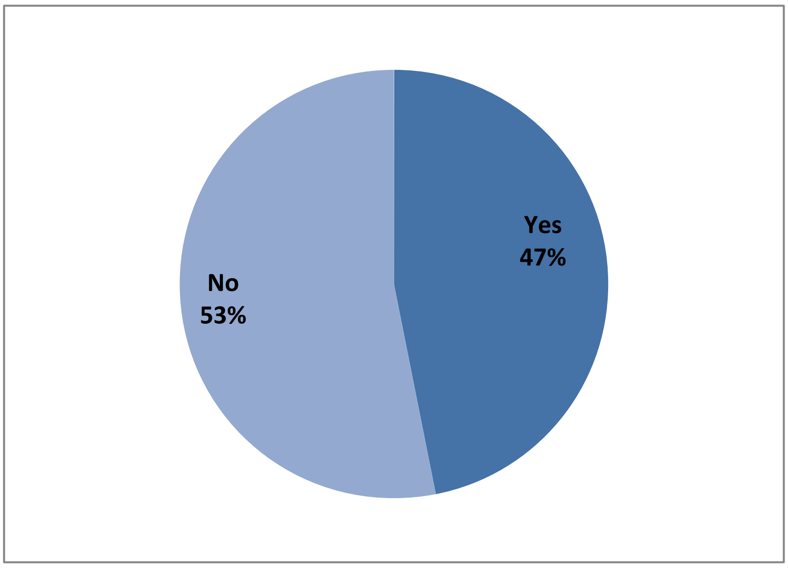


Figure 6.24 Results for whether choose evacuation routes based on accessibility of fire exit

The building installations such as fire alarms and the escape route signs also influenced the evacuation. It is reported that a “false alarm interpretation” leads to the performance of certain longer-delay evacuation and the ‘slow whooping’ signal is rarely recognised compared with the ‘spoken message sound’ signal. Virtually, the participants were told they can begin to evacuate if they in danger. It was noticed that sound signals had little effects in mobilising the evacuation. There were no significant differences between the effects of ‘slow whooping’ signal and ‘spoken message sound’ signal. It is true that the participant delayed the evacuation to make sense of the building situation (Section 4.2). The post questionnaire indicated that the sound source hardly pushed the participants to begin the evacuation if they felt they were in safety place (Figure 6.25). Indeed, the visual danger factors such as fire and smoke can more directly express emergency situations.

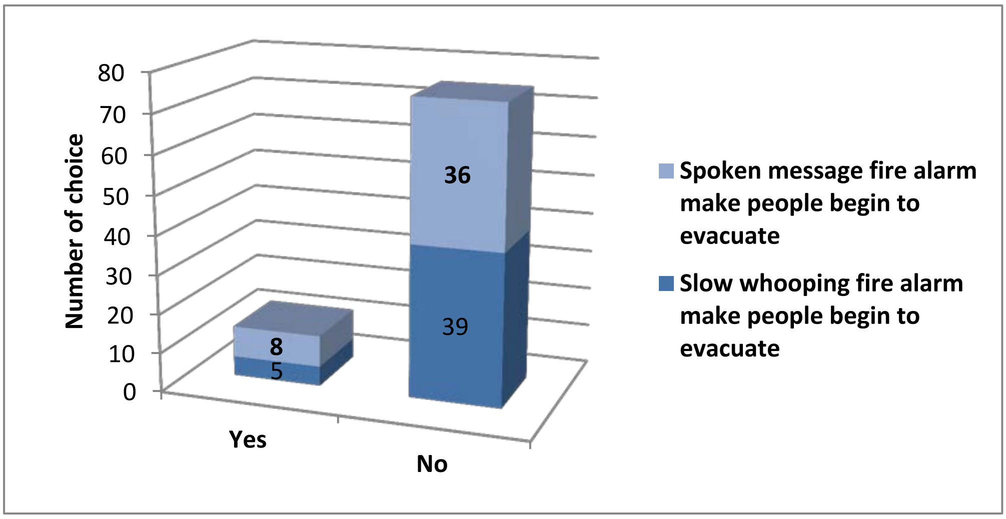


Figure 6.25 Investigation of whether 'slow whooping' and ‘spoken message’ fire alarm make participants begin to evacuate

The escape route sign are recognised as the traditional way to guide the occupations to the emergency exit during the fire emergency. However, the position of escape route sign (position marker) that allows evacuees to easy follow should be discussed. It was investigated by post questionnaire after virtual experiments because the BIM-VE was still developing the virtual environment for this research. Figure 6.26 illustrated the escape signs are easy to be observed at both higher and lower wall level. Similar to previous researches, ceiling level escape signs were hardly noticeable. From open questions, it was suggested that luminescent and highlight contrast coloured escape sigh should be installed to help the evacuees. The participants also suggested that it is necessary to use different colours lines on floors to direct the evacuees to the nearest emergency exit. This might be because they are more sensitive to the visual factors rather than audio factors.

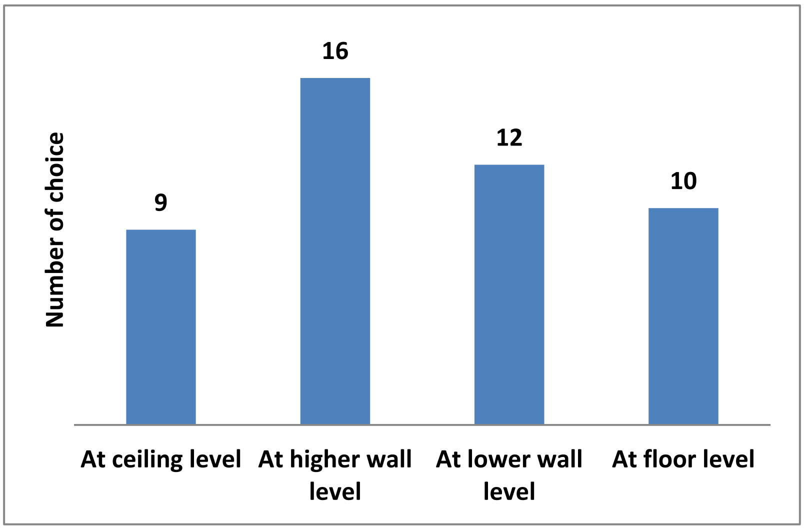


Figure 6.26 Which position of escape route sign/position marker can easy be noticed by evacuee

According to results above, the post questionnaire further explored which factors mostly influence the choice of evacuation route. Figure 6.27 shows the route familiarity and the evacuation guide sign played the most important in the choice of evacuation path. The route accessibility also influenced the participants to choose the evacuation route. People seldom evacuated considering firefighting facilities.

In terms of building layout influencing fire evacuation, there are still several aspects which the virtual experiments and questionnaires have not covered due to function limitation of the BIM-VE. These become the future development direction of the BIM-VE, which mainly focus on fire compartments, fire doors, and flammable materials. Specifically, the BIM-VE should create dynamic scenarios to test how fire compartment size and automatic closed fire door influence fire evacuation. To make fire spread as real as possible, the semantic information of flammable material for furniture and construction should be integrated with the adding fire function of the BIM-VE, which can crease self-spreading fire referenced to the circumstance materials for more vivid virtual environment. With experiment observation and questionnaire investigation, the reliable results can be further obtained.

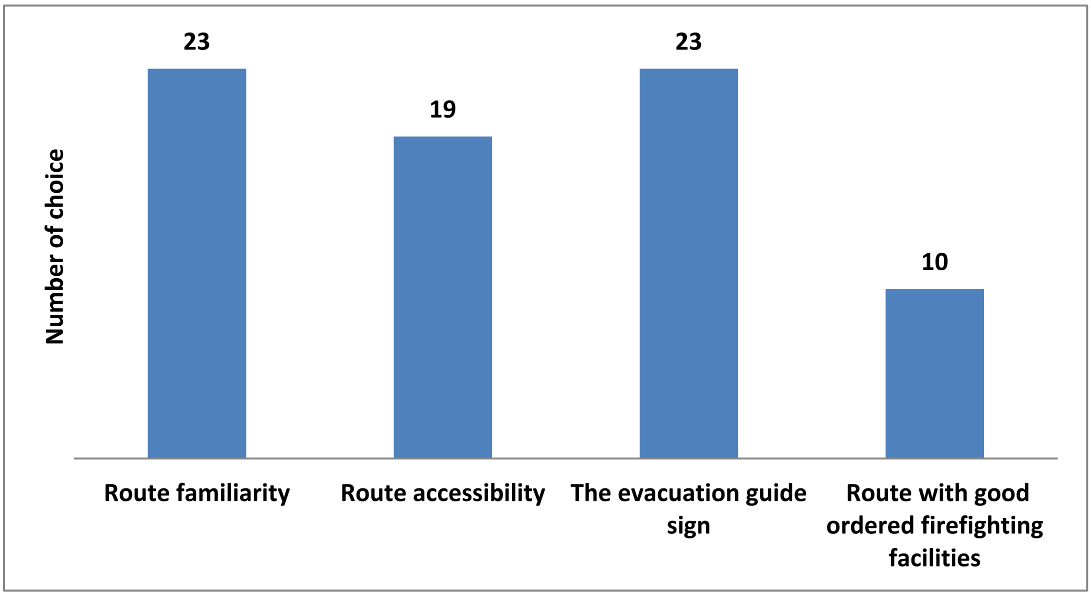


Figure 6.27 Which factors mostly influence the choice of evacuation route

6.2.5. Emergency factors: fire, smoke, and toxic gas

When people face emergency dangers such as fire, smoke, and toxic gas, they generally have three kinds of response (i.e. move through, turn back/left/right, or wait), which can be utilised to build the evacuation AI (artificial intelligence). In the virtual experiments, the responses of each participant were recorded, which were then utilised to calculate probability of different emergency response actions.

The average probability of participants' response is shown in Figure 6.28, which provide the base of evacuation AI in specific building to add fire evacuation dimension for building design in the future. It can be seen that the participant had a higher average probability (48%) to move through the jeopardy. A reason for this was the existence of avatar health bars, giving players the habit of risking of getting damaged on non-fatal occasions, or players thought the danger was acceptable when they began to evacuate. Moreover, it was observed that most participants turned back/left/right (31%) when facing the hazards at the beginning of the virtual fire drills. The participants only waited (21%) to judge the emergency situation when they faced extreme dangers such as a big fire accompanied by an explosion. Therefore, the result of the average probability of actions from this virtual experiment can only be used to building evacuation AI for less dangerous situations (i.e. the beginning of fire emergency).

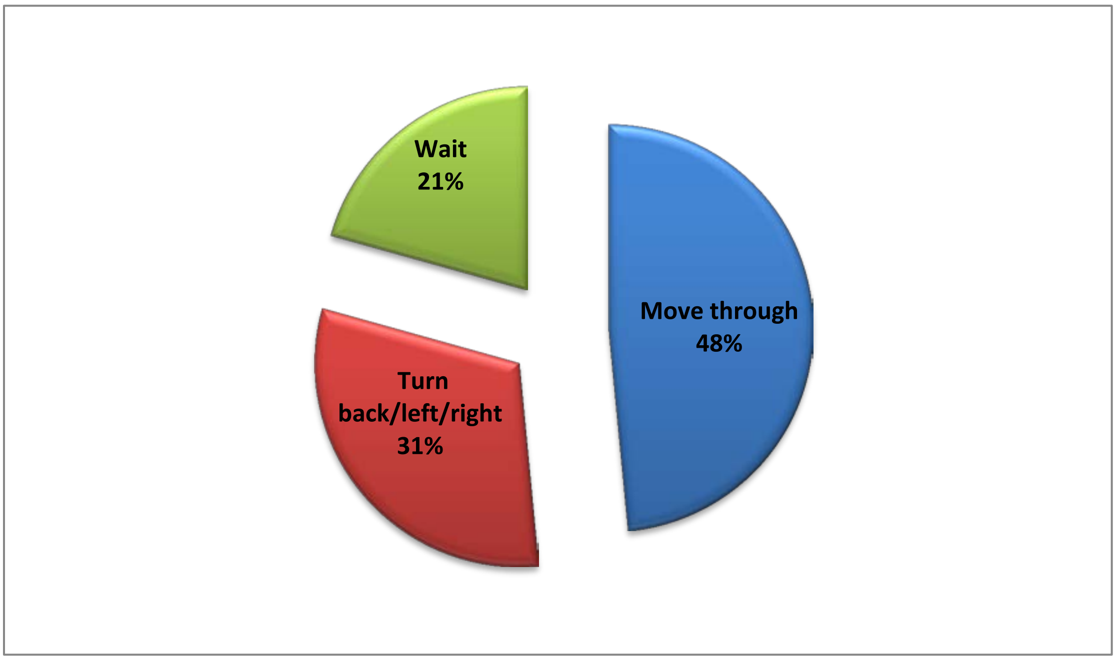


Figure 6.28 The average probability of different actions when facing the fire hazards (i.e. fire, smoke, toxic gas) in the virtual fire drills

Most avatars controlled by participants run alongside walls for guidance in the reduction of sight (e.g. in the smoke) and their running speed was slower than normal speed as well, this corresponding to the previous research (Lawson 2011). Figure 6.29 confirms this in the virtual fire drill: 91% participants were observed that they run alongside the wall for guidance with slower running speed. According to the statistics, 63% of those who run alongside walls in the reduction of sight were observed more than twice while 70% of those whose running speed was slower in the low visibility were detected more than twice. Both of them were evident in the virtual fire drills.

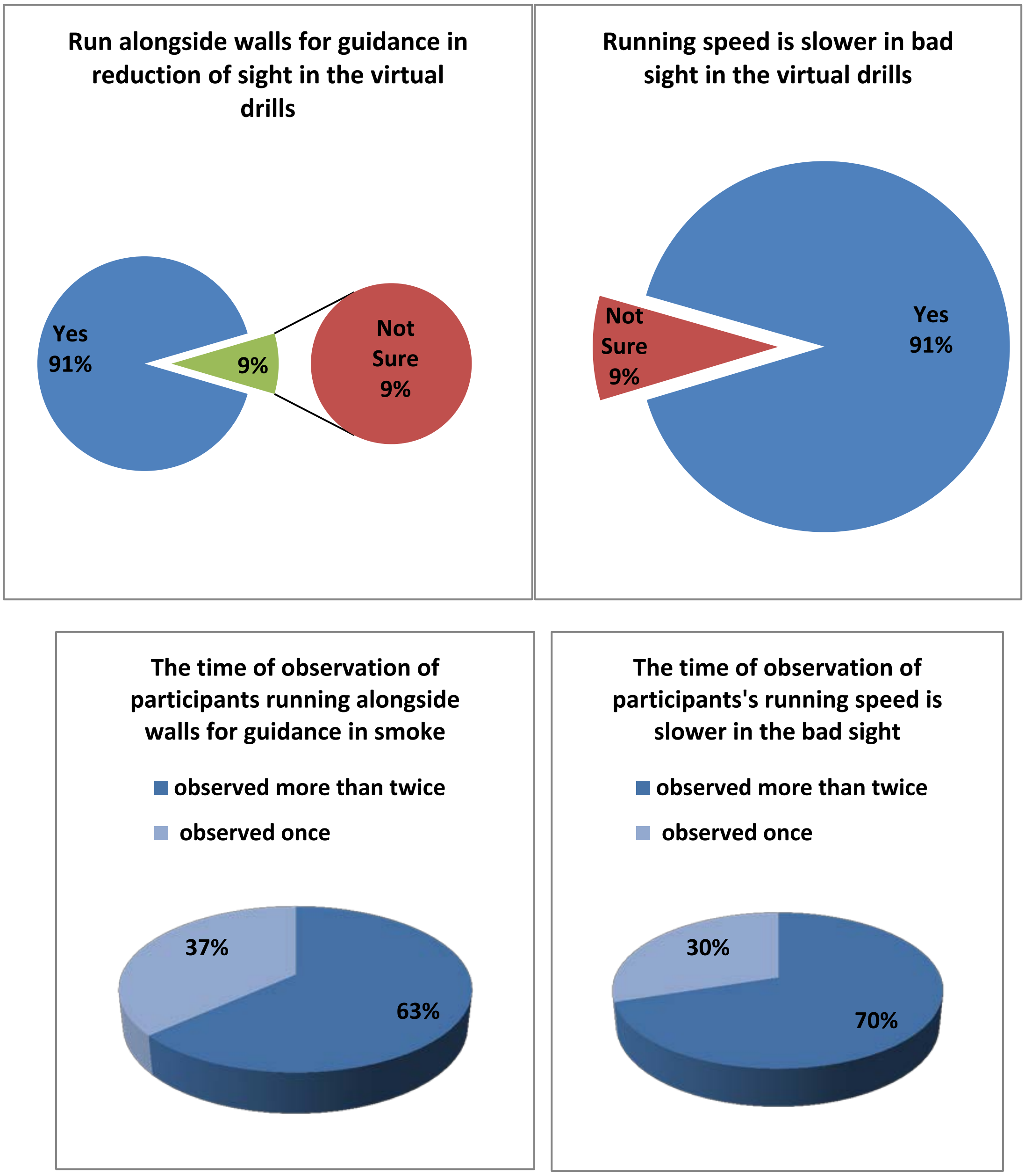


Figure 6.29 Investigation of human fire responds in the reduction of sight

To validate this, the experiment assistant allowed the participant to recall their behaviours in low visibility and finish the post questionnaire. Figure 6.30 shows the consistent result just like the results researched by virtual experiments. Most participants stated they tried to run alongside walls for guidance in the reduction of sight. The reason why the percentage (81%) of run alongside walls is lower than the result (91%) investigated by virtual drills is because some participants cannot recall and there were also an error range between virtual drills and questionnaire investigation.

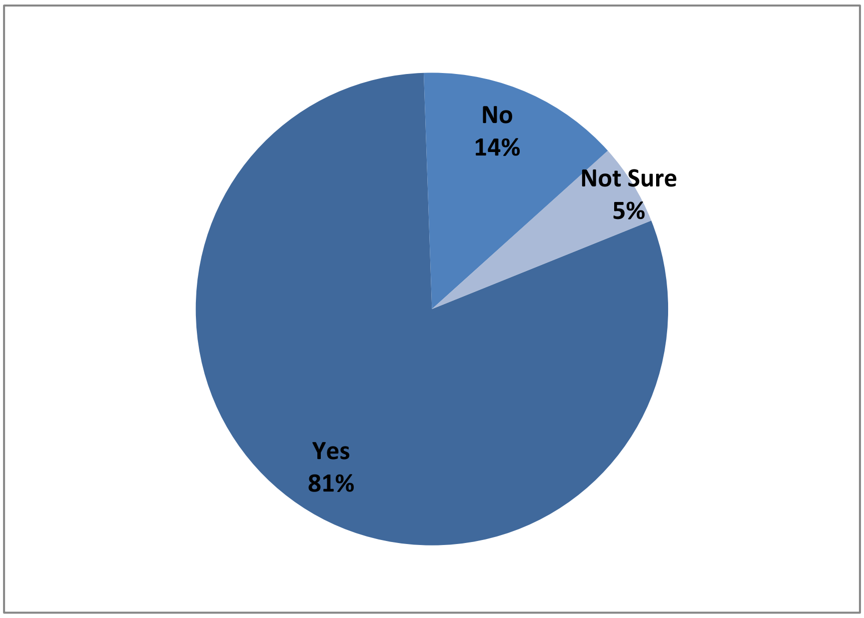


Figure 6.30 Investigation of whether evacuees walk alongside walls for guidance in the reduction of sight by post questionnaire

The post questionnaire further explored whether the participants have a trend to crawl through the smoke/toxic gas because the BIM-VE did not support crawl animation of avatar yet in the virtual experiments. Figure 6.31 shows that nearly half (47%) of participants were inclined to crawl through the smoke/toxic gas. A large portion (31%) of participants did not know whether they would crawl or not until they faced this emergency situation. Therefore, the crawl animation of avatar should be developed with suitable scenarios to enhance the accuracy of this result.

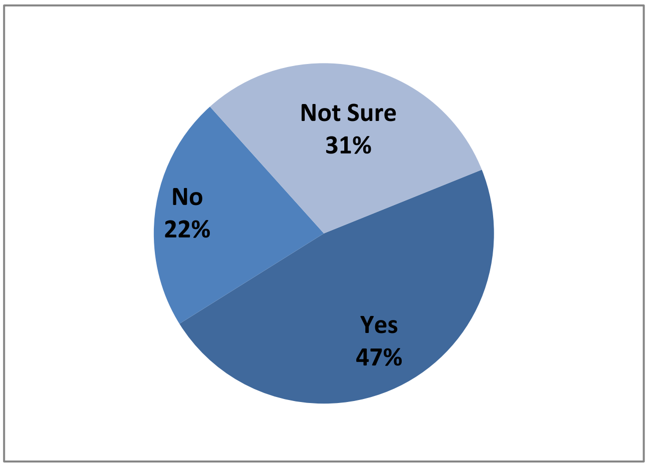


Figure 6.31 Investigation of whether evacuees have a trend to crawl through the smoke/toxic gas

The post questionnaire also investigated how fire size and growth influence the fire evacuation due to inconspicuous observation in virtual experiments. Only one participant choose fire size and growth would not influence his evacuation. He explained the reason was because he knows the building layout well and care more about the shortest evacuation route rather than emergency factors like fire. For most other people who though fire size and growth influenced their evacuation in virtual experiments, they stated that they chose the way out that looked like less dangerous (i.e. fire with small sized and slow growth) and normally evacuate following the opposite direction if they face big fire or explosions. However, they agreed that they might take risk to pass through the danger if they knew where to go or there was no way to go.

Although the BIM-VE already provided dynamic virtual experiments to validate and extend the factors influencing human fire evacuation, the experiment results are all for general people without disability. The BIM-VE has not considered the scenarios to test factors influencing people who have different levels of disability (high, low, temporarily reduced, and permanently reduced). Therefore, it becomes the future direction to utilise the BIM-VE to investigate how disabled people choose their evacuation way because it is even hard for them to participant in the real fire drill due to their mobility limitation.

Chapter 7 Conclusion

This PhD research targets at a BIM based virtual environment for both existing and new buildings with the aim to effectively involve the end-user throughout the building life cycle with a focus on building emergency management. The innovation lies on the seamless integration between BIM and the serious game, to leverage the semantic based dynamic scenario generation and dynamic path finding algorithms to provide real time information updating for evacuation guidance. By utilizing the comprehensive data resources hosted in BIM, end-users can be involved alongside with design professionals to achieve user-centred building emergency design, operation and management.

The appropriate research problem has been concluded at the beginning, and the corresponding research hypotheses and objectives have been proposed in order to achieve the research target. The developed system has demonstrated the appropriate solutions, e.g. a computer game system – Unity3D has been seamlessly integrated with a representative BIM design environment – Autodesk Revit through a real time two-way information channel. More individuals can therefore get involved in the decision making process during the early BIM based conceptual design stage.

By utilizing the comprehensive data resources hosted in BIM, general building end-users can work with professionals within the BIM-VE to achieve user-centred building emergency design and planning, and get real-time evacuation guidance on multiple platforms (including desktop, laptop, web browser and mobile devices) if there is a building emergency. During an emergency, 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 and emerging fire, playing a fundamental role in fire evacuation.

Another research target is to provide convenient training (to building users) to increase emergency awareness. The tested scenarios have also successfully demonstrated a good capability to train building users, allowing them to quickly get familiar with the building and locate the right evacuation route in both common platform (such as PCs and mobile devices) and virtual reality immersive platform (i.e. 3D projector with Razer Hydro joysticks system for publics and HMD with Windows Kinect system for individuals).

The system has been created and functionality has been tested. Through case studies, several emergency behaviour patterns have been identified for future fire evacuation design, which can help to identify and address the bottlenecks of buildings during early design stage. Several key fire evacuation factors have also been recognized through literature review, and further tested and analysed in the case studies.

Chapter 8 Further Work

The BIM-VE research prototype has been developed and tested. It proves the proposed research hypotheses and is able to get end-users better involved in the design decision making process to help achieve better building emergency planning and evacuation. The underlying system is generic and can be further developed and tested in a much large scale.

OpenBIM (IFC) Interfacing: Specifically, the current system works with Autodesk Revit and a specific data format (e.g. FBX and obj.) is required to transfer building information from the BIM to the serious game, which limits the current system to work with other BIM software packages. As Industry Foundation Classes (IFC) has been promoted as the de-facto standard for data and process interoperability in the AEC (Architecture Engineering and Construction) industry, one of the future works is to implement IFC interface alongside with Revit API to build a universal data component which fits for different BIM software packages. The first improvement would be that more of the parametric data could be extracted from the model permitting uses of the system in other areas such as using it for minor modifications of the structural elements of the building. Using IFCs would also allow for direct updating and integration of new elements into the model, which would simplify the process and potentially speed it up

Further improvement of two-way information transfer: another improvement is to resolve the issues that have occurred with two way information channel when updating the objects created/placed in the BIM-VE back to Revit. Analysis and debugging to resolve that could be potentially time consuming task. Besides, the current scope of inventory library to meet particular tasks/needs is limited. But it would become more powerful if the library connects to a database to download the standard (e.g. IFC based) furniture/building components via internet. Semantic information should enable the intelligent placement of building internal objects to allow for the selection of an internal layout. This could be implemented to work in a similar manner to the way that walls and doors can be placed and used in BIM applications such as Autodesk Revit. For example, a wall would use the properties of the rest of the building such as the floor and ceiling heights to work out where it should start and end in the vertical direction. Likewise a door for example would only be able to be placed on a wall rather than just in space.

New application developments: The developed system can potentially be used to provide real time indoor position services during a building emergency. However, large scale evaluations of the overall system and a full scale case study throughout the building life cycle are needed. The robust network framework to support fast and satisfactory data transmission during emergency situations needs to be investigated. New generation Indoor Position System (IPS) holds the potential to provide real time indoor position services during the building emergency, but due to the time and cost constraints, this has not been investigated in this research, hence would be a future research point. With regards to the path finding algorithm, the end-users with a disability might need the safest evacuation route rather than the shortest due to their movement limits. Hence, the specific path finding algorithm for their situation needs to be further developed. This research provides a platform with multi-functionality capability, several other applications like building energy consumption map, interior building and layout design, BIM based life cycle design and operation can be further developed and tested.

Smarter computer game character: **s**everal key knowledge regarding human behaviour under emergency situation have been concluded out of the first hand and comprehensive system testing; the preliminary ontology development has been conducted, but the result can be further extended and used to develop smarter testing game characters to conduct large scale (thousand representative characters with certain pre-defined human intelligence can be easily deployed into the system) fire evacuation compliance checking during the entire building life cycle, e.g. design, construction and operation stages to identity and timely rectify any potential bottleneck and limitation.

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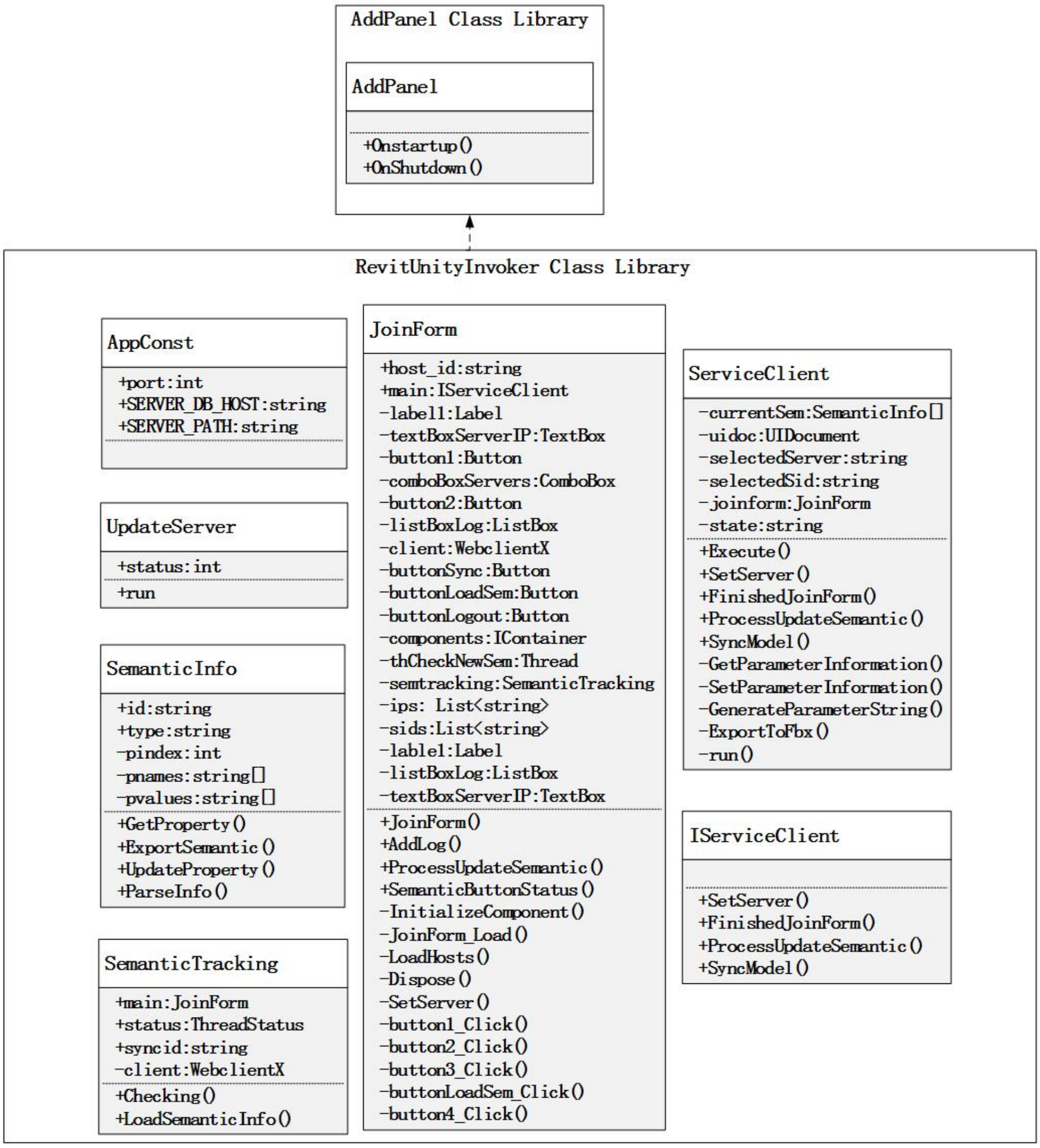
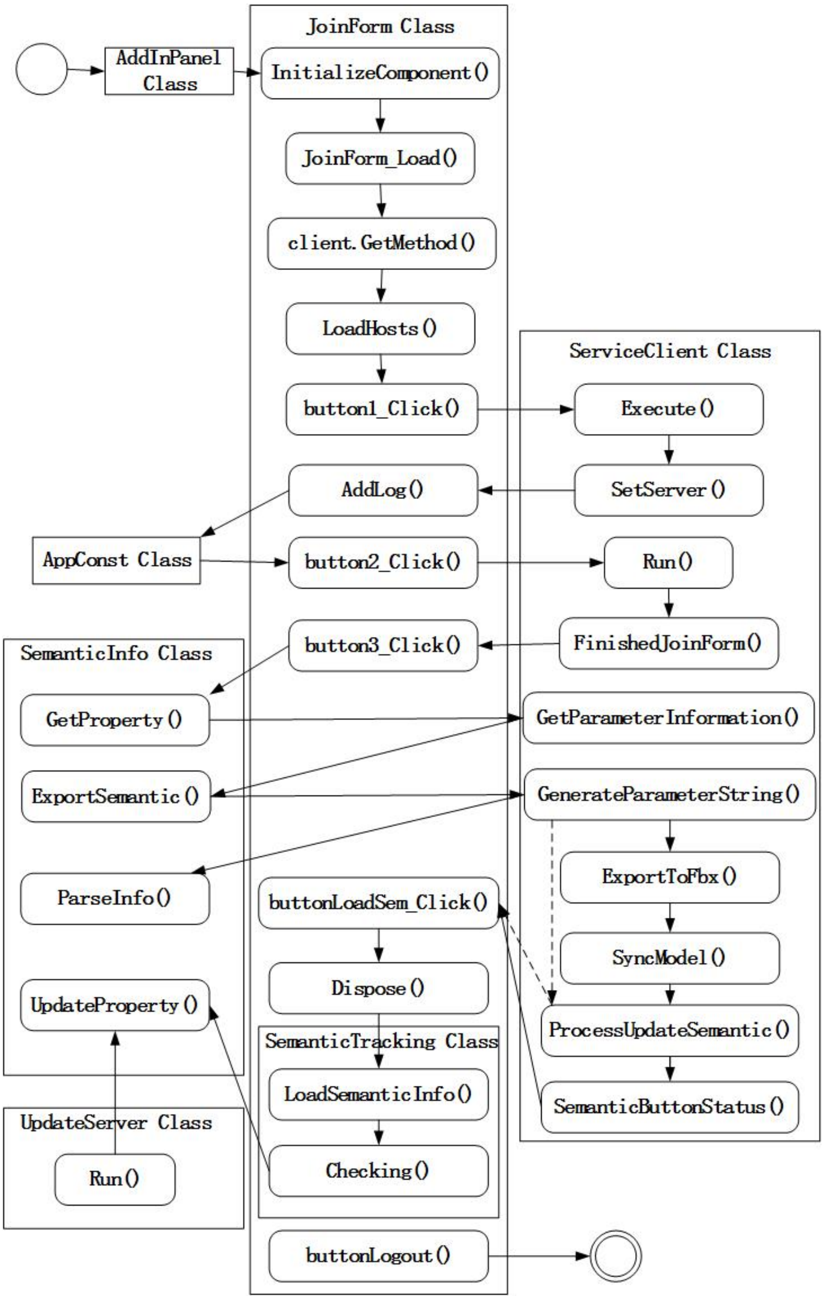
Appendix A BIM Software Survey

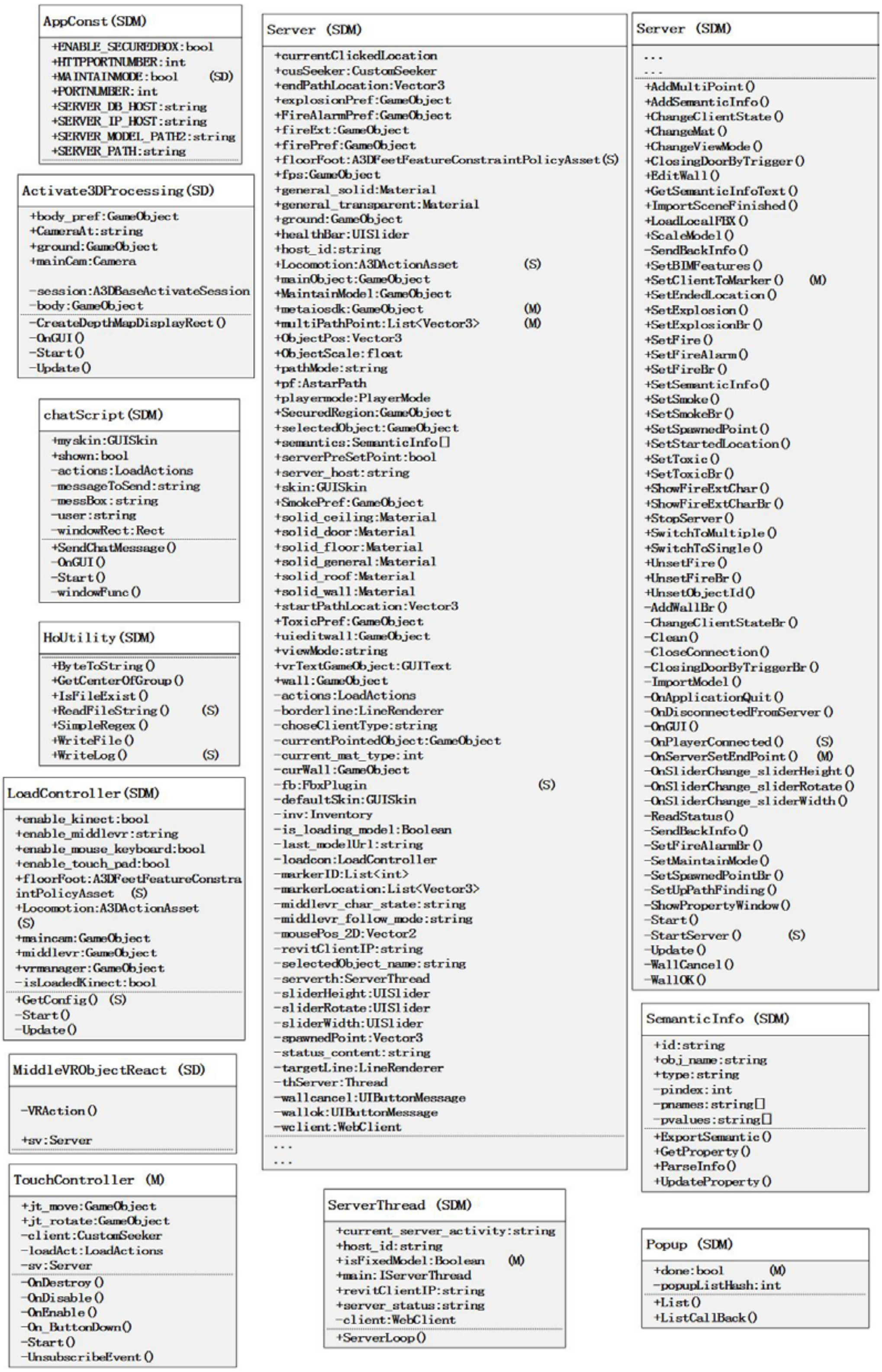
Appendix B Classes, methods, variables and their collaborations for purposes



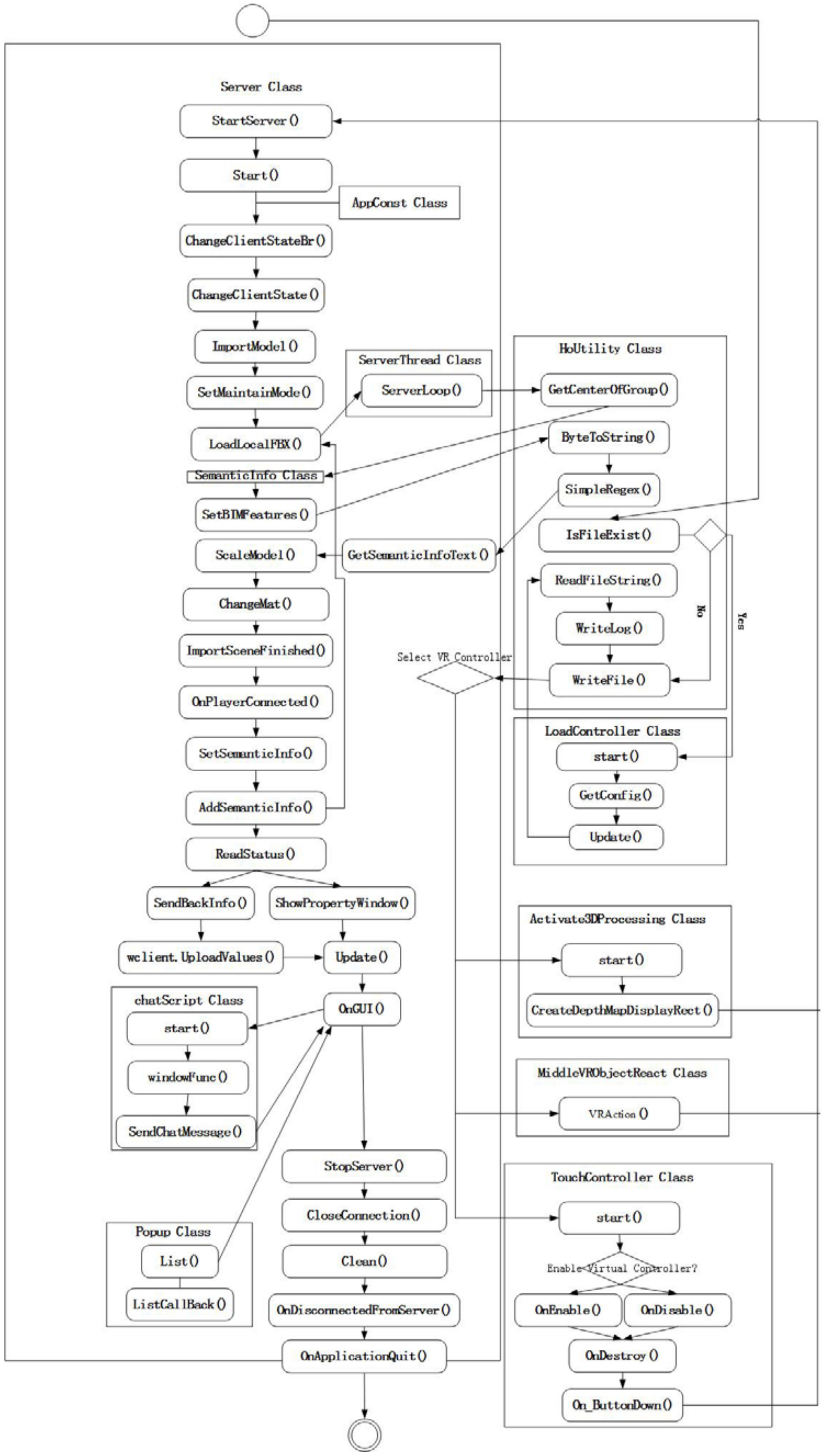
The class libraries that constitute the Revit plug-in



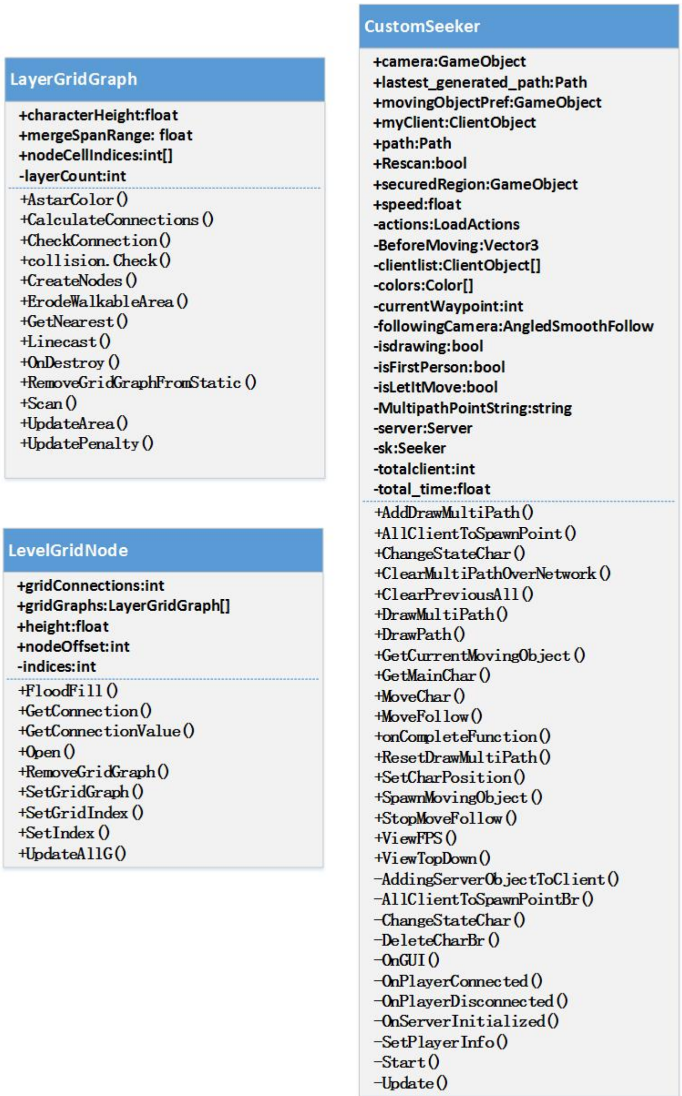
Basic classes and functions collaboration in Revit plugin



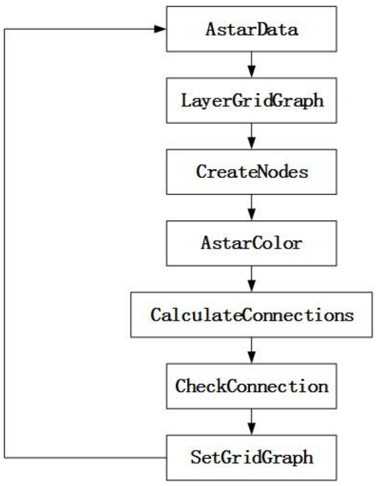
The class library for information transferal and functionality control within server-clients framework



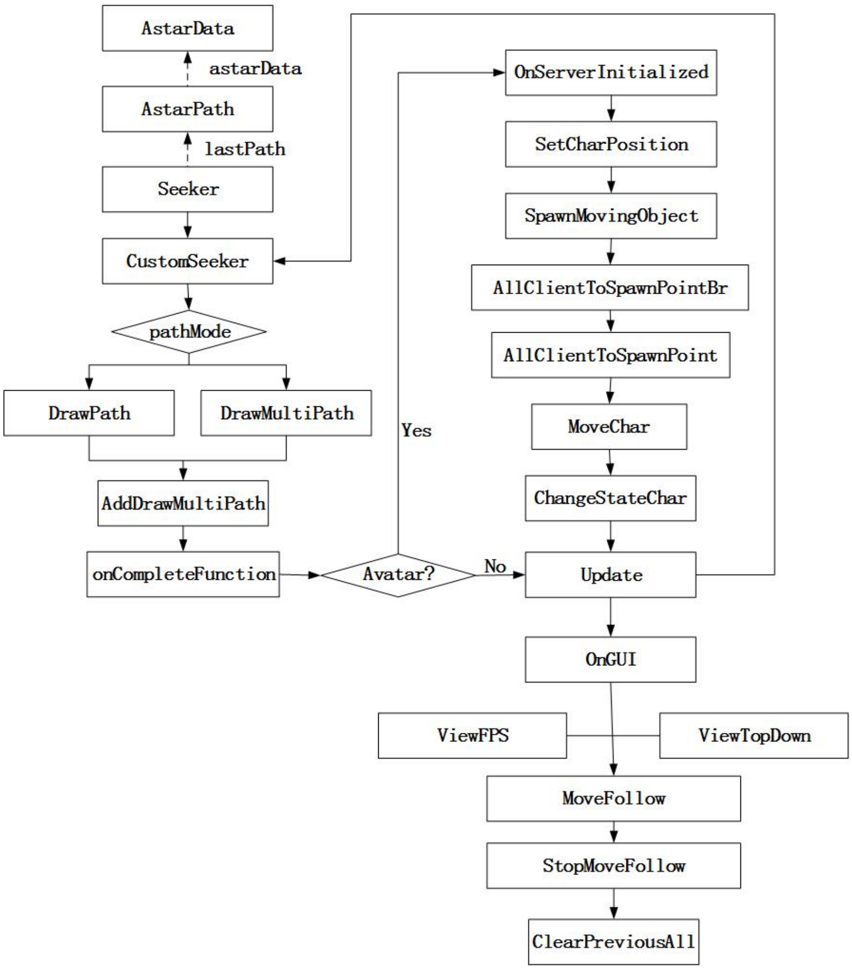
Basic classes and functions collaboration for information and functionality control within server-clients framework



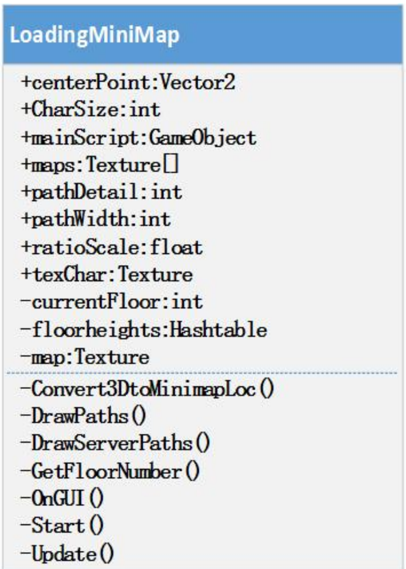
Classes to create evacuation path (i.e. 'LayerGridGraph', 'LevelGridNode and 'CustomSeeker')



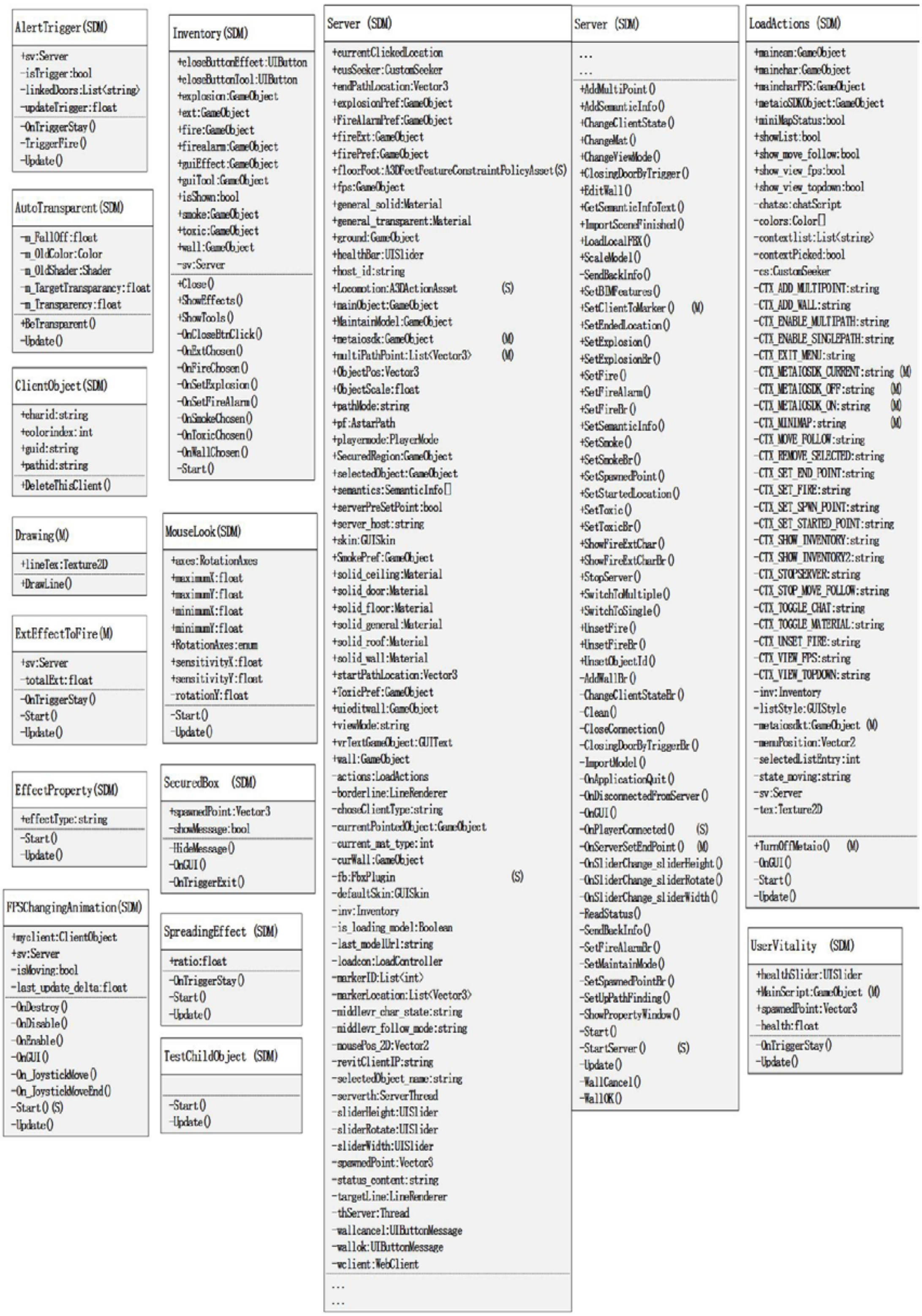
The flowchart of main classes and methods to generate coloured layered grid graph



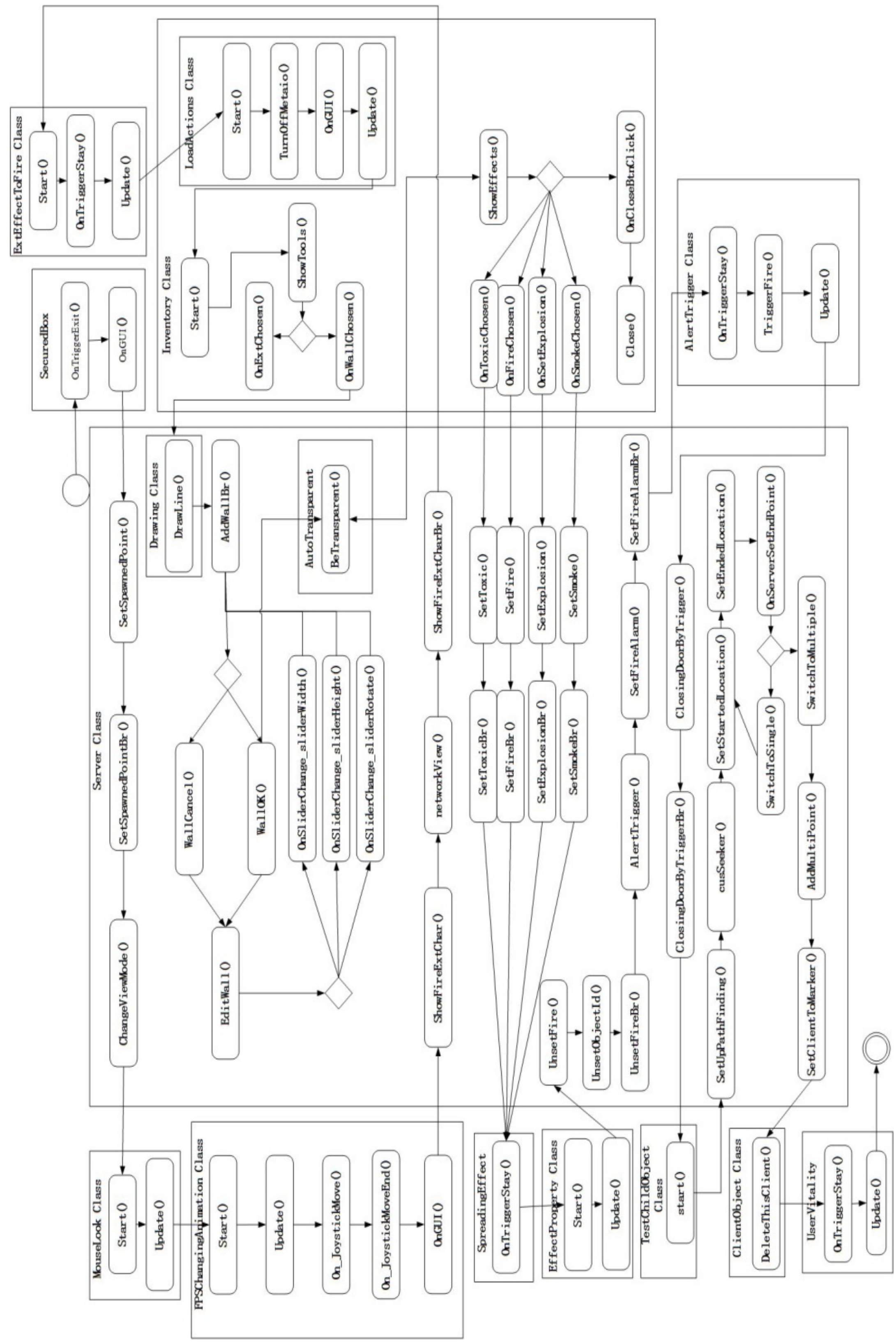
The flowchart of main classes and methods to create the evacuation path on layered grid graph and make the player follow them for evacuation guidance/training



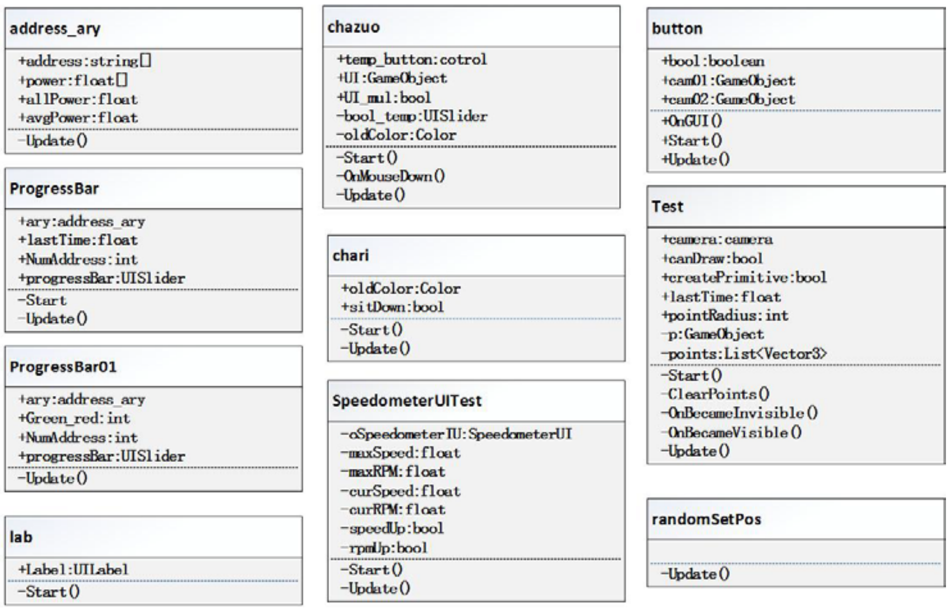
Main variables and methods to create minimap within the BIM-VE



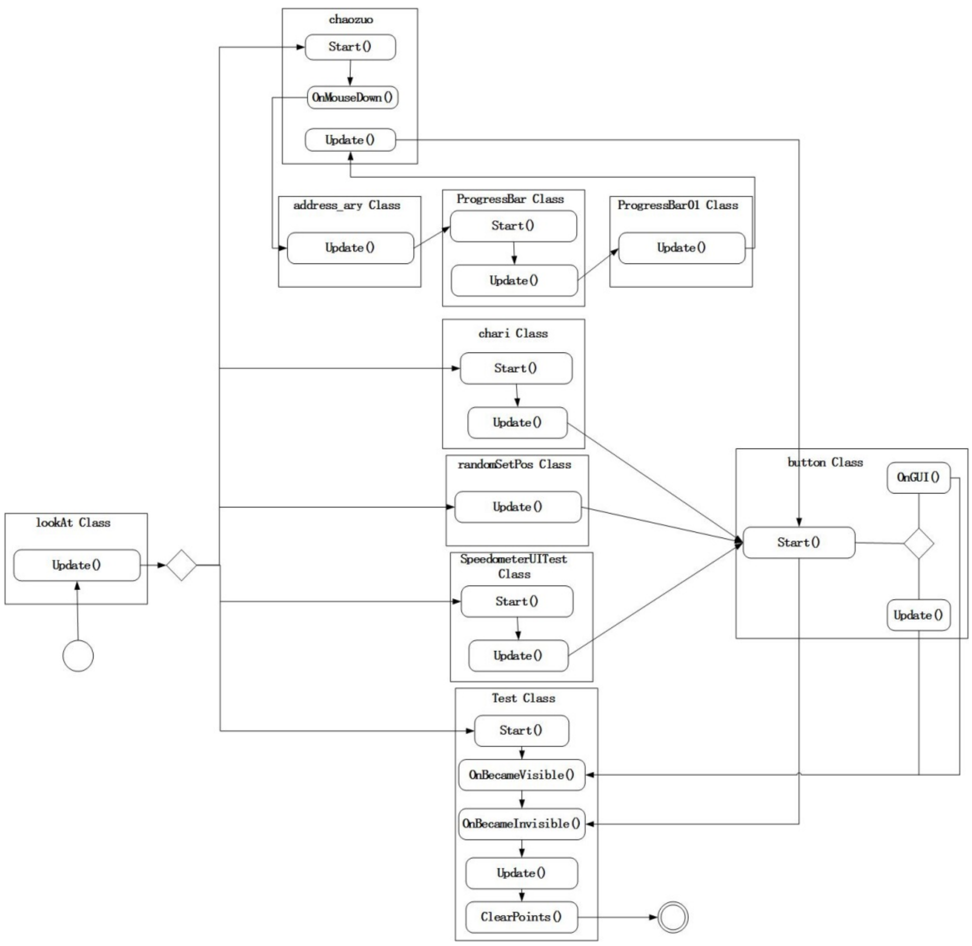
The class library for emergency evacuation guidance and training



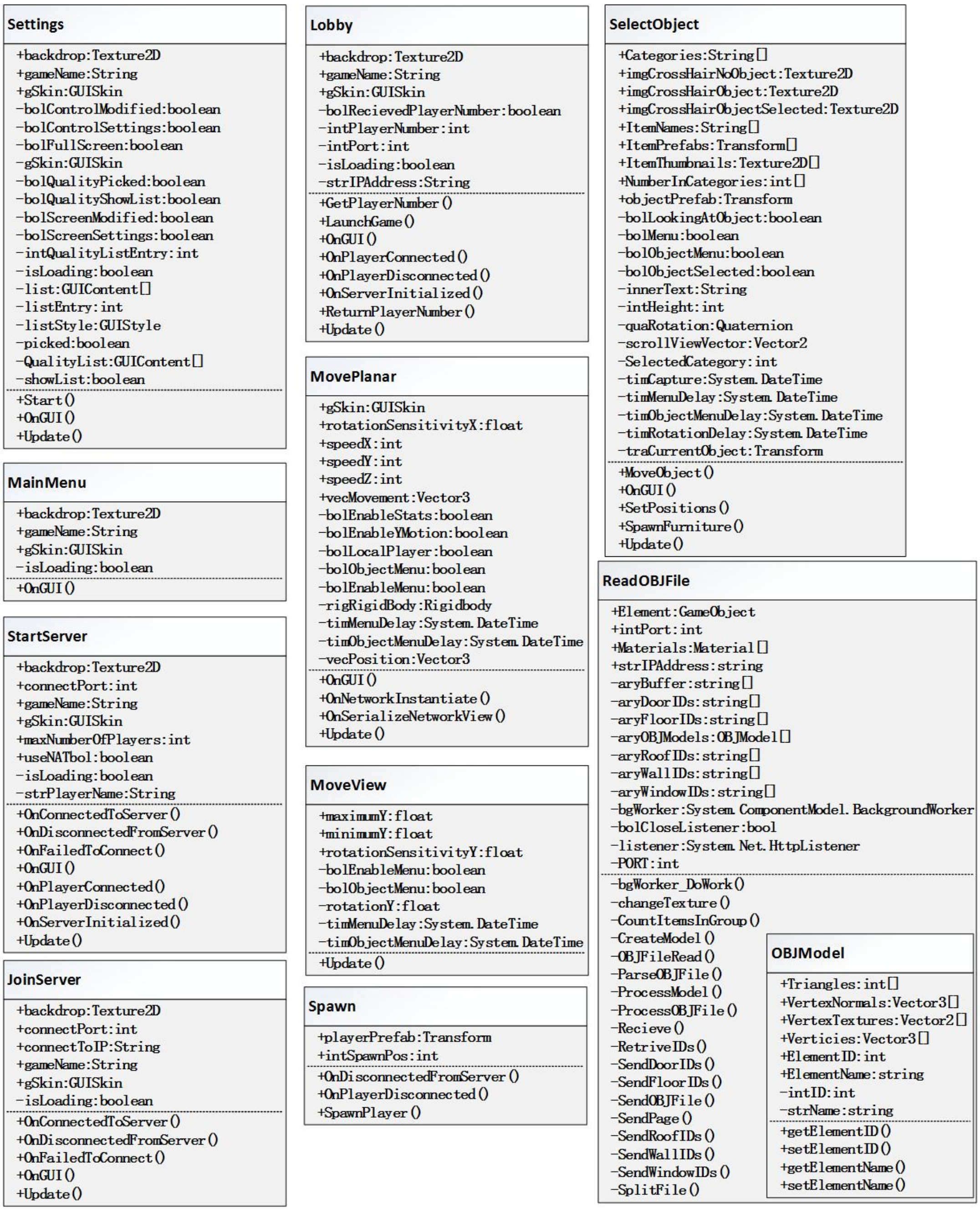
Basic classes and functions collaboration for emergency evacuation guidance and training



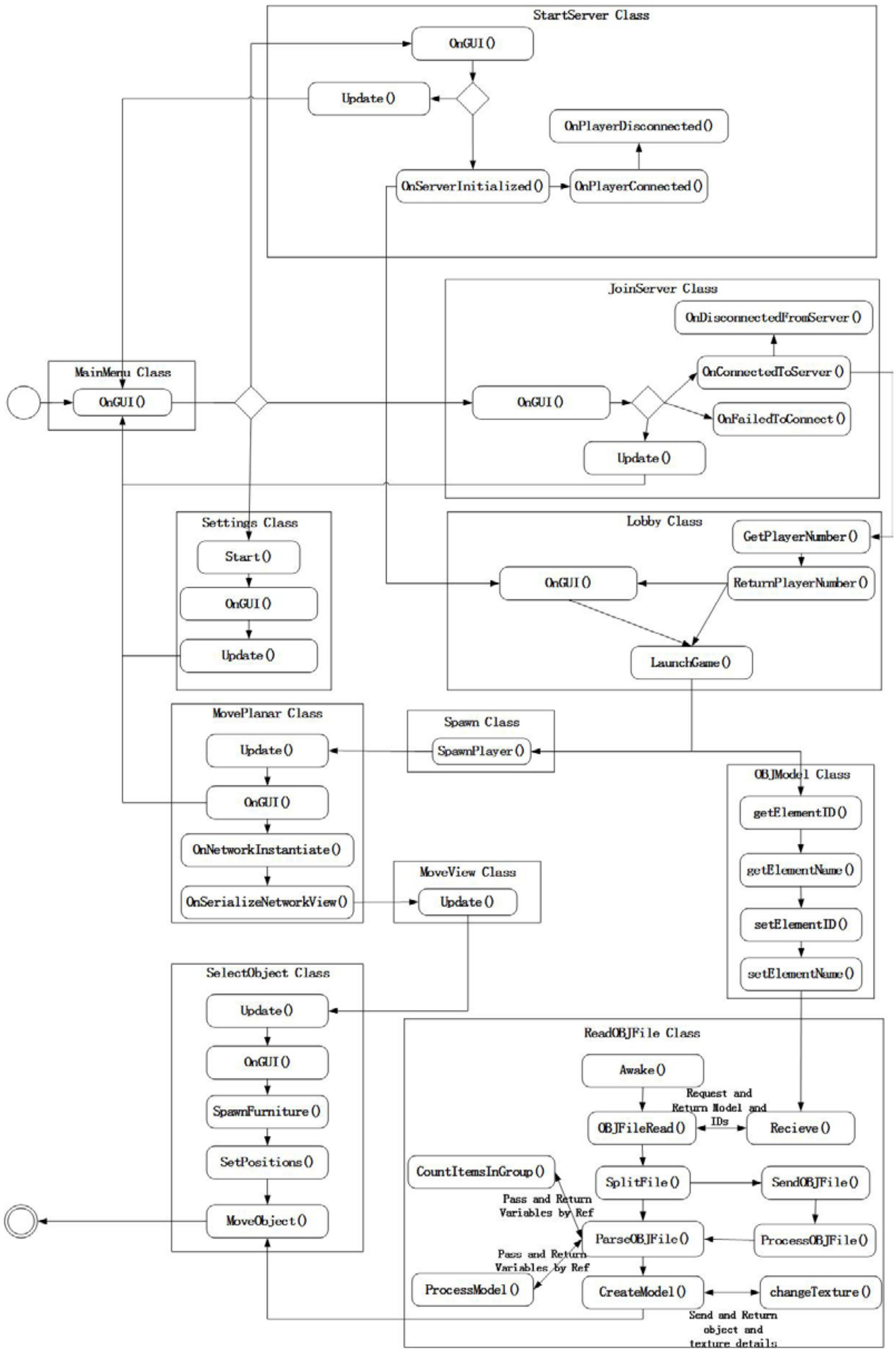
The class library for real-time building information visualization and monitoring



Basic classes and functions collaboration for real-time building information visualization and monitoring



The class library for user engaged building interior design



Basic classes and functions collaboration for user-centred building interior design

Appendix C Experimental Data and Result