AN INVESTIGATION INTO DATA SHARING BETWEEN BUILDING INFORMATION MODELLING AND FIRE SAFETY ENGINEERING, WITH POTENTIAL APPLICATIONS TO SMART BUILDINGS

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DECLARATION

"I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct."

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ABSTRACT

Building Information Modelling (BIM) is a relatively new digital data flow standard for the whole building lifecycle in the Architecture, Engineering and Construction (AEC) industry that suffers from existing problems such as data loss and incompatibilities on building projects. For Fire Safety Engineering (FSE) which is a safety support discipline, BIM presents an opportunity of integrated iterative design checking and support in evolving fire safety requirements during the life cycle of a building. However, the current support for FSE in BIM and vice versa has several limitations. For instance, a lack of explicit support for FSE based analysis data in BIM and only basic geometry extraction support for BIM data in some fire and evacuation modelling tools.

This study examined the key challenges in data sharing between BIM and FSE based analysis using fire and evacuation modelling tools and proposed a strategy to address them. This strategy proposed a step by step process targeting the limitations in BIM Industry Foundation Classes (IFC) Model specification, implementation of the specification in BIM design tools, and support for BIM in fire and evacuation modelling tools.

To support the strategy, development work was undertaken that included identification of the data requirements for FSE information exchange with BIM. A prototype database was then developed to capture this required data in a structured way. Based on the findings, recommendations were provided on enhancing BIM support in fire and evacuation modelling tools. A prototype system was also developed which with some limitations, successfully demonstrated data sharing between BIM and FSE using a selection of case studies. Furthermore, a conceptual design of a BIM-enabled Smart Signage Management System was presented as an example application of BIM with FSE data sharing in a Smart Building environment.

It is hoped the work presented in this study will assist in the development work for the proposed collaboration project which is currently in the initiation phase with BIM standards organisation buildingSMART, for FSE support in BIM IFC Model. If the proposal is accepted, then the proposed development work will have a direct impact on the future version of IFC specification. Moreover, it is hoped that if the recommendations presented in this study for enhancing support for BIM in fire and evacuation modelling tools are realised, the data sharing for FSE based analysis within the BIM context will significantly improve.

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
API	Application Programming Interface
ASET	Available Safe Egress Time
BACS	Building Automation and Control Systems
BAS	Building Automation System
BCF	BIM Collaboration Format
BCS	Building Control System
BIM	Building Information Modelling
BIoT	Building Internet of Things
BMS	Building Management System
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
CFD	Computational Fluid Dynamics
DBMS	Database Management Systems
DE	Decision Engine
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dose
FM	Facilities Management

FSE	Fire Safety Engineering
FSEG	Fire Safety Engineering Group
GUID	Globally Unique Identifier
HVAC	Heating, Ventilation, and Air-conditioning
IADSS	Intelligent Active Dynamic Signage System
IDE	Integrated Development Environment
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IoT	Internet of Things
ISO	International Standards Organisation
MEP	Mechanical, Electrical, and Plumbing
MVD	Model View Definition
NoSQL	Not only Structured Query Language
RDBMS	Relational Database Management Systems
RSET	Required Safe Egress Time
SQL	Structured Query Language
SSMS	Smart Signage Management System

1 INTRODUCTION

This chapter begins with the background information and motivations of this research study. The research questions and objectives are covered next which are then followed by an indication of the structure of this dissertation.

1.1 Background and motivation

The sharing of information in an effective way is essential on any project involving multiple contributors and stakeholders. The introduction of technology has significantly changed the way the information is shared. From paper-based to digital data flow, the use of technology has improved the process of data sharing and it will continue in that direction due to business demand and the evolving nature of the technology that facilitates it.

The use of digital technology has been around for years particularly in Aerospace and Automotive industries. The idea is to effectively manage data by having a digital representation of a physical asset. However, the Architecture, Engineering and Construction (AEC) industry which is the largest in the world (Lavikka *et al.*, 2018) is behind in the use of digital techniques as compared to other industries such as Aerospace and Automotive. The AEC industry is complex as it consists of many contributing disciplines which during building lifecycle, particularly at the design phase, share data to create specific project deliverables. In short, several sub-models for specific domains (e.g. Architectural and Structural models) of the same building project are created usually using various software tools to capture different aspects of design (Autodesk, 2013).

Fire safety in the built environment is of utmost importance and has the following objectives (ISO, 2018b):

- Safety of life,
- Property protection,
- Continuity of operations,
- Protection of the environment, and
- Preservation of heritage.

The national regulations or building codes consider life safety and protection of the environment as an essential requirement (ISO, 2018b). To ensure these objectives are met, two fire safety design methods are used. The first one is the Prescriptive method which uses a set of rules and applies them on the following two areas: 1) Egress design which is related to maximum length of routes, the width, number of exits, flow capacities, etc. and 2) Fire protection which is related to fire protection zone, placement of fire extinguisher, etc. The second fire safety design method is Performance based which unlike the traditional Prescriptive approach, applies an engineering approach to achieve the fire safety objectives. The main idea is to find the safe maximum time limit for evacuation and assess if the structure can be reasonably evacuated within this time period. By utilising modelling and simulations, the performance-based approach attempts to establish whether the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET) plus a specified safety factor. The ASET is driven by the fire development and often determined by a fire simulation model while RSET is driven by human behaviour and often determined by an evacuation simulation model. The safety factor is a multiplicative or additive adjustment applied to the calculated values to compensate for uncertainty in methods, calculations, input data and assumptions (ISO, 2018b). It should be noted that there is also a coupled ASET and RSET analysis approach where the impact of fire hazards on the population is taken on board. Although this approach is less common, it can provide more realistic results (Galea *et al.*, 2008). The first approach to calculating RSET value is like an evacuation drill where the whole population can get out because there are no hazards. In the second approach, i.e. the coupled ASET/RSET, the fire hazards can change the population behaviour and can cause casualties/fatalities if the occupants experience severe enough conditions.

Fire Safety Engineering (FSE) is the Performance based approach which is understood to be an "*application of scientific and engineering principles to the protection of people, property and the environment from fire*" (BSI, 2002). FSE is a relatively young but evolving safety support discipline which takes a wide range of data input from other disciplines and utilises fire, evacuation and structural modelling tools for analysing the fire safety aspects of a structure. The multi-disciplinary nature of the data (Architecture, Engineering, Physics, Computer Science, Chemistry, Psychology, Physiology, Economics, Mathematics and Statistics) makes FSE complex (FSEG, 2013) but also highly connected with other domains. The role of FSE is key in analysing the fire safety aspects of a building particularly during the design phase, in case of a change in building usage as well as for structural and forensic analysis.

For analysing the fire safety aspects using FSE, fire and evacuation modelling tools are utilised. These modelling tools, depending on their capabilities, may require detailed data input covering various aspects of the building, including the geometry of the building design, material information, nature of the occupancy, number and nature of the occupants, evacuation routes, type of alarm, and fire and smoke management systems. Moreover, the fire and evacuation analysis results, produced by these tools are shared with architects and designers so that the design can either be approved or improved as appropriate.

Currently, there are several issues in managing data on construction projects amongst various contributing disciplines including FSE in terms of how the data is shared, data accuracy and level of detail. This not only has serious time and cost implications on projects but particularly from the FSE perspective can pose a threat to human life. The lack of digital data flow is an important factor behind these problems. The Hackitt Report (Hackitt, 2018) which is an independent report commissioned by the UK Government after the Grenfell Tower fire in June 2017, has made a number of recommendations including a need for a *"golden thread of information"* to be embedded throughout the entire building lifecycle. This means recording and preserving information throughout the building lifecycle with any changes going through a formal review process. With this in mind, it is important to mention here the currently widely used approach to building design in the AEC industry called Computer-Aided Design (CAD) or Computer-Aided Design and Drafting (CADD) which uses computer technology for design and design documentation (Autodesk, no date). When it was introduced, the CAD approach was a step forward from the hand drafted drawings and blueprints as it offered improvement by representing lines as vectors based on mathematical equations which allowed portions of a drawing to be twisted, stretched, or moved. However, the CAD approach has several significant limitations.

Building Information Modelling (BIM) is a relatively new but evolving standard for sharing and managing data digitally for a built environment. Its aim is to apply the digital data flow and management approach in the AEC industry that has been successfully utilised in other industries. The limitations of CAD technology can be addressed by BIM. For instance, unlike the simple lines and curves associated with traditional CAD approach, BIM offers an object-based, rich in data, and intelligent digital representation of the facility. As well as being described by dimensions and locations, objects (e.g. walls and doors) also have data attached relating to materials and compositions. In short, BIM software contains the physical and functional characteristics of the building in fields of data in a database, rather than lines and text in a CAD file, which makes it a lot easier to update and retrieve data.

The AEC industry is highly fragmented and slow to adapt to change. It suffers from various problems such as software interoperability, version control, information accuracy, projects routinely exceed schedule/budget, claims and litigation (Jones, 2012). The introduction of BIM can tackle these problems but the idea of moving from CAD to BIM is a major change for the AEC industry. This is because this shift requires not only a change in approach but also it means the initial cost implications of staff training. However, BIM has strong backing from various governments particularly the UK who is one of the leaders in delivering active support for BIM. The UK Government Construction 2025 vision (HM Government, 2013) considers BIM as an integral part of its aspiration for UK Construction in order to deliver more sustainable buildings, more quickly and more efficiently. The Hackitt Report (Hackitt, 2018) has also recommended the use of digital techniques offered by BIM. Furthermore, as far as BIM standards are concerned, the worldwide authority is buildingSMART (buildingSMART, no date a) which is a neutral, open and not-for-profit organisation. It also promotes the idea of Open BIM (buildingSMART, no date e) and is responsible for setting standards to deal with the process, data, management, etc. in the built environment. It is worth mentioning a couple of important aspects of BIM. The first one is the data model called Industry Foundation Classes (IFC) which is an International Standards Organisation (ISO) standard (ISO, 2018a). The IFC Model is highly structured consisting of four layers that contain building elements. One of the layers is called the Domain Layer which caters for specific data related to certain domains, for instance Electrical domain and Architecture domain. The IFC is primarily used not only for describing but also for sharing and exchanging building data between various tools working with BIM. The second aspect is BIM vision which is represented using the BIM Evolution/Maturity diagram created by Bew and Richards in 2008. This diagram captures evolution from CAD to BIM and represents progress through levels 0 to 3. The aim of BIM is to reach Level 3 which is meant to offer a fully integrated single shared model held in a centralised repository.

From an FSE perspective, BIM presents an opportunity of integrated iterative design checking and support in evolving fire safety requirements, not only during the design phase but also the extended life cycle of a building. Furthermore, the combination of BIM with FSE can potentially lead to automation that can play an important role in future Smart Buildings (also referred to as Intelligent Buildings) i.e. buildings that use automated systems to control the building operation to achieve required levels of efficiency, comfort and/or safety for the occupants. For example, in the future, the combination of BIM and FSE in a Smart Building environment can potentially identify near optimal evacuation information (Grandison *et al.*, 2017) for building occupants in response to an evolving emergency incident (Galea, Xie, *et al.*, 2017). However, this will only be possible if the current limitations in BIM with FSE data sharing are addressed.

In case of BIM, even though it has evolved and gone through a significant improvement which has resulted in increased support by the professionals and BIM product vendors, a number of issues and limitations such as difficulty finding BIM skilled staff and managing complex digital information have been reported in the National BIM Report (NBS, 2018). On the other hand, FSE is multi-disciplinary, complex and does not have its own domain specific sub-model unlike the Architectural model, Structural model, etc. This may be because FSE does not create the building's physical elements but instead use mainly the Architectural model for analysing fire safety aspects. It can impact on how and where these physical elements can be used and therefore FSE's role is critical. For FSE, several fire and evacuation modelling tools are available in the market but there is no single independent organisation controlling standards and as such, there is no one standard data exchange format for sharing simulation data between various tools. The support for FSE in BIM and vice versa has a number of limitations (e.g. lack of support for FSE based analysis data in BIM and limited support in fire and evacuation modelling tools for BIM) in terms of data sharing which should be addressed to allow stakeholders to make more informed, focused and relatively quick decisions on building's key fire safety aspects.

A holistic approach is needed to fully realise the potential benefits of FSE with BIM data sharing by resolving the current deficiencies. However, at present, there is a limited effort to develop a systematic integration of FSE within BIM. This study examines the key aspects including current challenges in data sharing between BIM and FSE based analysis using fire and evacuation modelling tools and proposes a way forward to address them. This work will not only provide an effective way to utilise current BIM effectively with FSE but also recommend future directions for BIM development. The development work carried out in support of this study serve as a proof of concept. Furthermore, this study also looked at the potential of using BIM with FSE combination in a future Smart Building environment.

1.2 Research question, objectives and approach

In order to understand and tackle the digital data flow enabled by BIM in building projects from the FSE perspective, the research question was:

How can effective data sharing be achieved between BIM and FSE based analysis using fire and evacuation modelling tools?

The above question consisted of several sub-questions which are mentioned below:

Question 1a: What are the essential data input and output requirements for FSE based analysis using fire and evacuation modelling tools?

Question 1b: What current level of support is there in BIM for FSE based analysis using fire and evacuation modelling tools?

Question 1c: What current level of support is there in fire and evacuation modelling tools for BIM?

Question 1d: Can a strategy be defined to address the limitations in data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

Question 1e: How to demonstrate data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

An area of application of this research is its potential implication on future buildings, for example, applications to Smart Buildings. To address this, the following two additional sub-questions were identified:

Question 1f: What level of support do Smart Building systems have in BIM?

Question 1g: Can a suitable conceptual design be outlined that can utilise BIM and FSE based analysis using fire and evacuation modelling tools in a Smart Building environment?

Research objectives and approach

The following objectives were set to aid in answering the research question through specific tasks:

1. Identify FSE information exchange within the BIM context. This objective comprised of the following sub-objectives:
   1.1. Identify data input and output requirements for FSE to use with fire and evacuation modelling tools, and the level of data sharing between them.
   1.2. Identify the level of support in BIM for essential input and output data for FSE for use with fire and evacuation modelling tools.
   1.3. Identify the level of support in fire and evacuation modelling tools for BIM.

   To partially address Objective 1 above which is related to Sub-questions 1a, 1b and 1c, the following tasks were performed:

   - Review relevant literature on BIM, FSE and the data sharing situation between them.
   - Based on the review, identify gaps in knowledge and limitations.

2. Formulate a suitable strategy to address the identified gaps in knowledge for data exchange for FSE within the BIM context to use with fire and evacuation modelling tools.

   To address Objective 2 above which is related to Sub-question 1d, the following tasks were performed:

   - List and describe each step of the strategy.
   - As part of the strategy, produce a list of main FSE data requirements for information exchange with BIM. This task was linked with Objective 1 as well.
   - Create a database schema to capture the identified data.

3. Provide a proof of concept for the proposed strategy by implementing a prototype system using suitable case studies.

   To address Objective 3 above which is related to Sub-question 1e, the following tasks were performed:

- Create a prototype database based on the database schema produced for Objective 2.
- Design and implement a prototype system for testing data sharing between FSE and BIM.
- Test the prototype system using selected case studies, prototype database, and the representative examples of fire and evacuation modelling tools.

4. Suggest enhancements in fire and evacuation modelling tools in support for BIM.

   To address Objective 4 above which is related to Sub-questions 1d and 1e, the following task was performed:

   - Based on the literature review related to Sub-question 1c and testing of the prototype system related to Sub-question 1e, suggest enhancements in fire and evacuation modelling tools.

5. Identify current support in BIM for Smart Building Systems and based on that propose a conceptual design of an application that utilises the combination of BIM and FSE within a Smart Building environment.

   To address Objective 5 above which is related to Sub-questions 1f, 1g and 1c the following tasks were performed:

   - Review relevant literature on Smart Building systems and identify their support in BIM.
   - Based on the review, present a conceptual design of a suitable application that uses a combination of BIM and FSE in a Smart Building environment.

Thesis contribution to Knowledge

Impact on the BIM standard: This study has opened the door for the possibility of a collaboration project on the development of a Model View Definition (MVD) for FSE. If the proposal is accepted by the BIM standards organisation buildingSMART then the development work will have a direct impact on the future version of IFC specification. The first part of the proposed MVD development work will be the identification of the information exchange for FSE. The following development work which was part of this study can assist in finalising the FSE information exchange requirements:

- The FSE based analysis preliminary database schema and its sample implementation for the proposed FSE information exchange within the BIM context. This database captures the key fire safety analysis data generated by fire and evacuation modelling tools.
- A prototype system using a suitable test case building as an example to demonstrate data sharing between BIM and FSE by utilising the development work as part of the proposed strategy. This system provides proof of concept for the proposed strategy.

<u>Recommendations for enhanced support for BIM in fire and evacuation modelling tools</u>: The recommendations made as part of the proposed strategy for enhancing the capabilities of fire and evacuation modelling tools such as SMARTFIRE (Ewer *et al.*, 2013) and buildingEXODUS (Galea, Lawrence, *et al.*, 2017) will improve support for BIM.

1.3 Structure of Thesis

Chapter 2: In Chapter 2, a literature review covering the key contents of this study, as stated in research questions and objectives, is presented. This review addresses BIM and FSE from the following perspectives: 1) BIM as an option for sharing and managing data digitally for a built environment, 2) FSE as a safety support discipline that can work with BIM, 3) Current data sharing situation between BIM and FSE based analysis using fire and evacuation modelling, and 4) Role of BIM with FSE in a future Smart Building environment. At the end of Chapter 2, key findings with an indication of gaps in knowledge are presented.

Chapter 3: The key challenges and limitations facing the use and contribution of FSE in the context of BIM, as identified in Chapter 2 are addressed in Chapter 3 through a strategy.

Chapter 4: In Chapter 4, the development work in support of the strategy for BIM with FSE is covered. Each step of the strategy which was covered in Chapter 3 is further discussed from the development work perspective. This also served as a proof of concept work for various aspects of the strategy. For each step of the strategy, the development work covering requirements analysis, design and implementation are discussed. Also, how the implementation work can be evaluated as part of the proof of concept work is presented. Furthermore, the conceptual design of an application of BIM with FSE combination in a Smart Building environment is discussed.

Chapter 5: The prototype system presented in Chapter 4, is tested using suitable case studies and the results are presented in this chapter.

Chapter 6: In Chapter 6, the main conclusions of this research are presented. The research questions and objectives set out in Chapter 1 are then reviewed in light of these main conclusions. Finally, a description of future development to enhance the presented work is provided.

2 LITERATURE REVIEW

2.1 Summary

In this chapter, a literature review is conducted covering the research questions on the topic areas of this research, as stated in Chapter 1. This review addresses BIM and FSE from the following perspectives: 1) BIM as an option for sharing and managing data digitally for a built environment, 2) FSE as a safety support discipline that can work with BIM, 3) Current data sharing situation between BIM and FSE based analysis using fire and evacuation modelling, and 4) Role of BIM with FSE in a future Smart Building environment.

The literature review covers the background, benefits, current level of support and the future trends particularly focusing on the data sharing between BIM and fire and evacuation modelling tools as part of FSE based analysis. Additionally, background, benefits, current situation and the future trends of Smart Building systems are covered focusing on whether their combination with BIM and FSE can offer a positive contribution in the future.

The purpose of this review is to identify gaps in knowledge which can be addressed by this research by gaining an insight into BIM, FSE, suitability and the level of data sharing between them, and can they play an important role in a future Smart Building environment.

2.2 Building Information Modelling

Building Information Modelling (BIM) is a relatively new term in the AEC industry which is a subject of some confusion and variation. As such, it is also called the Building Information Model (National Institute of Building Sciences, 2007) and even Building Information Management (Weygant, 2011). There is no single agreed definition of BIM, but the following is widely quoted:

"A digital representation of the physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward." (National Institute of Building Sciences, 2007).

The article by Quirk (2012) has provided a brief history of BIM particularly as far as the conceptual idea is concerned. First, after highlighting that *"BIM software must be capable of representing both the physical and intrinsic properties of a building as an object-oriented model tied to a database"*, the article then went on to state that *'the conceptual underpinnings of the BIM system go back to the earliest days'* i.e. 1962 of computing and gave reference to Douglas C. Englebart's vision of the future architect in his paper 'Augmenting Human Intellect'. Some background to Visualising the Model and Database Building Design was also included followed by Virtual Building and Collaborative Architecture.

The 'History of Building Information Modelling' article (The BIM Hub, 2014) mentioned Chuck Eastman, Tom Maver, Arto Kiviniemi, John Mitchell and Robin Drogemuller as the five early researchers of BIM processes and technology. Eastman's contribution to the concepts behind BIM was highlighted in his 1975 paper called '*The use of computers instead of drawings in building design'* which included a description of a working prototype named as Building Description System (BDS). Development work continued around the world and in 1986, the term Building Modelling was first documented by Robert Aish. The term '*Building Information Model'* was first documented by Van Nederveen and Tolman in their 1992 paper titled 'Modelling multiple views on buildings'. However, it was ten years later when the term BIM gained popularity after the release of the white paper by Autodesk. Jerry Laiserin who has been credited for promoting the term BIM provided background and history of BIM in the Foreword section of (Eastman *et al.*, 2008). According to him *"Building Information Modeling was not an innovation attributable solely to any individual or entity"*. Nevertheless, he highlighted the contribution of Chuck Eastman, Robert Aish, G.A. Van Nederveenand and F. Tolman.

Before proceeding to further information about BIM, it is important to mention here the CAD approach to building design which is still widely used in the AEC industry. CAD is the use of computer technology for design and design documentation (Autodesk, no date). The following description is based on Craven (2018). Architects and others use CAD software to create plans and construction drawings. Prior to CAD, drawings and blueprints were drafted by hand. Unlike the hand-drawn approach, CAD software records lines as vectors based on mathematical equations. This means portions of a drawing can be twisted, stretched, or moved. In short, the picture will automatically adjust based on these changes. CAD Software (e.g. AutoCAD, TurboCAD, and Vectorworks) usually includes support for various features including the following:

- Switching between Two-dimensional (2D) and Three-dimensional (3D) views.
- Zoom in and out facility.
- Rotation of images to view them from different perspectives.
- Change of image scale.
- Data in the CAD drawings are graphical entities only, such as lines, arcs and circles which are usually looked at using DWG (Drawing) or DXF (Drawing eXchange Format) files. The DXF file format is a standard file exchange format that is used by many different CAD and graphics programs. This allows users to exchange drawings even if they do not have the same program. However, the DXF file format has numerous versions which can cause problems for import unless the target software supports all/the latest versions. On the other hand, the DWG file format is a proprietary format of AutoCAD.

CAD technology has several problems which are mainly related to geometry limitations. Some of these problems are:

- Misuse of layers and bad scaling (can lead to inappropriate objects such as wiring, furniture, etc., being interpreted as geometry and causing errors in the interpretation of the geometry),
- Building might not match plans,
- No clash detection (clash detection prevents problematic and expensive on-site conflicts between various components and sub-systems in the design,
- Very complex with multiple layers,
- Often only 2D which means missing height information for doors/windows/ceilings/etc.,
- No filtering of detail (unnecessary and fine scale detail can massively increase the complexity and cost of supporting simulation modelling, with no practical benefits to the analysis of the design.), and
- Version compatibility issues.

In relation to CAD, the current situation in the AEC, the largest industry globally, is that it is highly fragmented and slow to adapt to change (Jones, 2012). Some of the key problems the AEC industry suffer from are software interoperability, version control, information accuracy, projects routinely exceed schedule/budget, claims and litigation (Jones, 2012). The introduction of BIM is to tackle these problems.

Earlier on it was mentioned that BIM is a subject of some confusion but Eastman (Eastman *et al.*, 2008) provided some clarification by first acknowledging that the terms Building Information Modelling and Building Information Model are often used interchangeably. For instance, The National BIM Standard (NBIMS) Initiative (National Institute of Building Sciences, 2007) categorised the Building Information Model in three ways: 1) A product, 2) An IT enabled, open standards based deliverable, and a collaborative process, and 3) A facility lifecycle management requirement. Furthermore, (Eastman *et al.*, 2008) stated the following which does not utilise the BIM technology:

- Models that contain only 3D data and limited or no object attributes i.e. the only purpose is graphic visualisation and lack of object level intelligence.
- Models lacking support for behaviour i.e. by not utilising parametric intelligence, positioning or proportions of objects cannot be adjusted.
- Models that are composed by defining the building using a combination of multiple 2D CAD reference files.
- Models that do not automatically ensure that changes made to dimensions in one view are reflected in other views.

2.2.1 Benefits of BIM

Table 2.1 has a list of some benefits of BIM mostly based on the following: (Mott MacDonald, no date a; Taylor *et al.*, 2009; Jones, 2012; McGraw Hill Construction, 2014).

Table 2.1: Benefits of BIM

	Benefit	Description
1	Information rich data	BIM offers object-oriented, data-rich, and intelligent digital representation of the facility. As well as being described by dimensions and locations, objects (e.g. walls and doors) also have data attached relating to construction materials and compositions. This is very different from the lines and curves approach used by CAD.
2	Collaboration	All project stakeholders from different disciplines, use preferably a single shared 3D model by utilising the collaborative working approach of BIM.
3	Single fully integrated model	BIM offers a single repository of all knowledge and information about a building through the whole life of the building from conception to demolition. This concept of BIM supports the idea of an embedded "*golden thread*" of information throughout the entire design process recommended by the Hackitt Report (Hackitt, 2018).
4	Reduced waste and lower construction costs	To enable effective handling of waste recovery and materials, the BIM model can be used for automated fabrication of equipment and components.
5	Improves visualisation	The same data can be represented in different ways due to easier transitions.

	Benefit	Description
6	Facilitates easier update, maintenance and retrieval of data	BIM software contains the physical and functional characteristics of the building in fields of data in a database, rather than lines and text in a CAD file. This makes it a lot easier to update and retrieve data because the objects will maintain a link with the data that defines their properties/behaviour.
7	Faster project delivery	A significant amount of time can be saved by utilising the intelligence within the model. For instance, design conflicts can be identified and resolved early in the project instead of costly resolutions at the construction phase.
8	Enhanced performance	By using BIM, it is possible to make a quick and accurate comparison of different design options.
9	Entire building lifecycle management	BIM creates digital DNA for a building that can stay current for its entire lifecycle.

2.2.2 Data exchange approaches and standards for BIM

The key reason behind the introduction of BIM in the AEC industry was to enable efficient digital information exchange and sharing between different applications used by various stakeholders during all phases of the building lifecycle (Isikdag, 2012). However, to represent building models, BIM applications used proprietary data formats. To resolve this interoperability issue, open BIM standards have been developed (Svetel, Jarić and Budimir, 2014).

2.2.2.1 BIM data sharing standards

The worldwide authority for BIM standards is buildingSMART which is an open and not-for-profit organisation (buildingSMART, no date a). It is responsible for setting standards to deal with built-environment related aspects such as process, data, change coordination for the specification, etc. OpenBIM which uses the open buildingSMART Data Model is an initiative of buildingSMART and supported by various leading software vendors. The focus of this approach is to use open standards and workflows for collaborative design and operation of buildings. The details of these standards (Process Standard - Information Delivery Manual (IDM), Data Standard - Industry Foundation Classes (IFC), Change Coordination - BIM Collaboration Format (BCF), and Mapping of Terms - International Framework for Dictionaries (IFD)) are available from (buildingSMART, no date e).

The National Institute of Building Sciences (NIBS) in the USA is a non-profit, non-governmental organisation and the buildingSMART Alliance is part of its Coordinating Council. They have listed various Information Exchange projects (East, no date) which have a consensus-based, technical specification consisting of a statement of requirements and the resulting technical specification. The requirements are defined in an IDM and are translated into a Model View Definition (MVD) or IFC View Definition that provides the technical description of which parts of the IFC Model found in ISO 16739 are needed to solve the problem.

2.2.2.2 Industry Foundation Classes

Industry Foundation Classes (IFC) is a data model which is an open file and an industry standard for describing building data. IFC is predominately used to share/exchange building data between proprietary BIM tools. To ensure BIM data can be read by all parties who are part of a project, regardless of the software they are using, the IFC Data Model was developed. The industry consortium buildingSMART is responsible for developing and maintaining IFC (Building, 2014c). The IFC specification is written using the EXPRESS data definition language which is defined as ISO10303-11 by the ISO TC184/SC4 committee (buildingSMART, no date b).

The IFC aims to provide data exchange without information loss among all AEC applications. It has full details including a graphical representation of all building components and their relationships with each other (Svetel, Jarić and Budimir, 2014). An important aspect of IFC is that the information is separated into two parts, namely geometry (can accommodate various geometric conditions) and data (can incorporate the physical properties such as material and weight associated with a particular object) (Building, 2014b).

The initial work on IFC started in the mid-90s. The following are the key points in the history of IFC development (Liebich, 2013):

- IFC 1.0 to IFC 2.0 (prototypes use: 2000 to 2002)
- IFC 2x to IFC 2x2 (adopters use: 2002 to 2008)
- IFC 2x3 (in use: 2008 onwards)
- IFC 4 (from 2014 onwards)

A broad review of the key stages of the IFC standardisation process prior to IFC4 is provided by Laakso and Kiviniemi (2012). The IFC Level of Maturity diagram by buildingSMART Canada (buildingSMART Canada, no date) provides an overview of the evolving and growing nature of IFC where it reaches the expected level of maturity. At that stage, it may be replaced or included in another standard.

The current major version of IFC i.e. IFC4 was released in March 2013 after 6 years approx. 8 person/year direct development effort (Liebich, 2013). Since IFC4 in 2013, for IFC version 4.0, a couple of addendums (IFC4 Add1 and IFC4 Add2) and a technical corrigendum for version 4.0 were released. The IFC4 Add1 released in 2015, incorporates essential improvements that were identified during the pilot implementations and the development activities for the first MVDs. In 2016, the IFC4 Add2 was released what incorporates essential improvements requests prior to starting the IFC4 certification process for the IFC4 Reference View and the IFC4 Design Transfer View particularly improved geometry definitions (buildingSMART, 2016a). IFC was also registered as the ISO 16739:2013 (revised as ISO 16739-1:2018) standard (ISO, 2018a). In 2018, IFC 4.1 was released which included support for the infrastructure aspects. Also, at the time of writing, candidate standard IFC4.2 was released in 2019 (buildingSMART, 2019b). A description of the basic structure of the IFC Model for IFC 2x3 and IFC4 is included in Appendix A.

IFC exchange files structure and format

IFC data files are exchanged between applications using various formats (buildingSMART, no date b) which are listed below:

- ifc: This is the default IFC exchange format with ifc extension and uses the STEP physical file structure according to ISO10303-21.
- ifcXML: It has xml extension and uses the XML document structure. An ifcXML file is usually 300-400% larger than an ifc file.
- ifcZIP: It has a zip extension and uses the PKzip compression algorithm. It offers a high level of compression by normally compressing an ifc by 60-80% and an ifcXML file by 90-95%.

2.2.2.3 Other approaches and formats

IFC is the main open standard exchange format for BIM which can include everything in a building. However, not everyone involved in a building project wants to know everything about a building (East, 2014). This is the reason why the MVD concept which was mentioned previously makes logical sense. Related to this idea, there are other open standard data exchange formats which are used for sharing of a more specific part of building data. Even though there are several building data exchange formats, only the two widely used ones are mentioned here:

Construction Operations Building Information Exchange (COBie): COBie is an information exchange specification for providing data required by facility managers. It is a common data format for publishing BIM data in a structured format. It allows capturing of data such as equipment lists, product data sheets and maintenance schedules (Building, 2014c). A COBie file can be viewed in various software packages including in spreadsheets which makes it a suitable option for all types of projects (National Institute of Building Sciences, no date). For background and history behind COBie, see (National Institute of Building Sciences, no date).

Space and equipment system-to-system exchange information can be provided by COBie and in several formats conforming to IFC COBie MVD. On the other hand, if there is a need to look at the COBie data directly then a translation of data into a spreadsheet approach is used (East 2014b). The COBie MVD identifies all the COBie relevant objects in IFC and the relationship between them.

COBie is part of NBIMS-US, version 2 which was published in March 2012. Also, the UK government BIM Task Group published the COBie UK 2012 version which is part of the level 2 BIM requirement (Building, 2014c).

Green Building XML (gbXML): The gbXML open schema (Green Building XML, no date) provides a way to transfer building properties stored in BIM to engineering analysis tools. The development of gbXML was started by Green Building Studio, Inc. in 1999 and was submitted in June 2000 for inclusion in aecXML (the industry-led initiative launched by Bentley Systems). The first version of the gbXML schema was published in June 2000 and since then several updates have been released. Even though IFC is the preferred format for data exchange, gbXML is an alternative format for interoperability to transfer information relevant to energy analysis packages. The advantage of making these two standards interoperable is mainly in terms of flexibility and choice of design or analysis application for designers. The availability of this option should be beneficial for the relevant users (National Institute of Building Sciences, 2008).

The gbXML is supported by leading vendors such as Autodesk, Graphisoft and Bentley. Also, major engineering analysis tools have integration modules in support of gbXML (Green Building XML, no date).

It is worth mentioning that an information exchange project by NIBS called the Energy Information Exchange (ENERGie) project was initiated to harmonise the requirements of gbXML and Leadership in Energy and Environmental Design (LEED) building elements, within the context of an EnergyPlus compliant MVD so that energy analysis specific information can be exchanged (National Institute of Building Sciences, 2008).

2.2.3 BIM current situation and future trends

In this section, the following points are covered: BIM Maturity Diagram and levels, support for BIM, and current BIM limitations and issues.

2.2.3.1 BIM Maturity Diagram and levels

The BIM vision is captured using the BIM Evolution/Maturity diagram, created and refined during 2008 by Mark Bew of buildingSMART and Mervyn Richards of Co-ordinated Project Information committee (CPIc). The diagram is an illustration of the evolution from CAD to BIM. Several versions of this diagram have been produced by various people to emphasize particular aspects of development and support (Snook, 2009).

The commonly used version is shown in Figure 2.1 (source: Bew and Richards 2008).

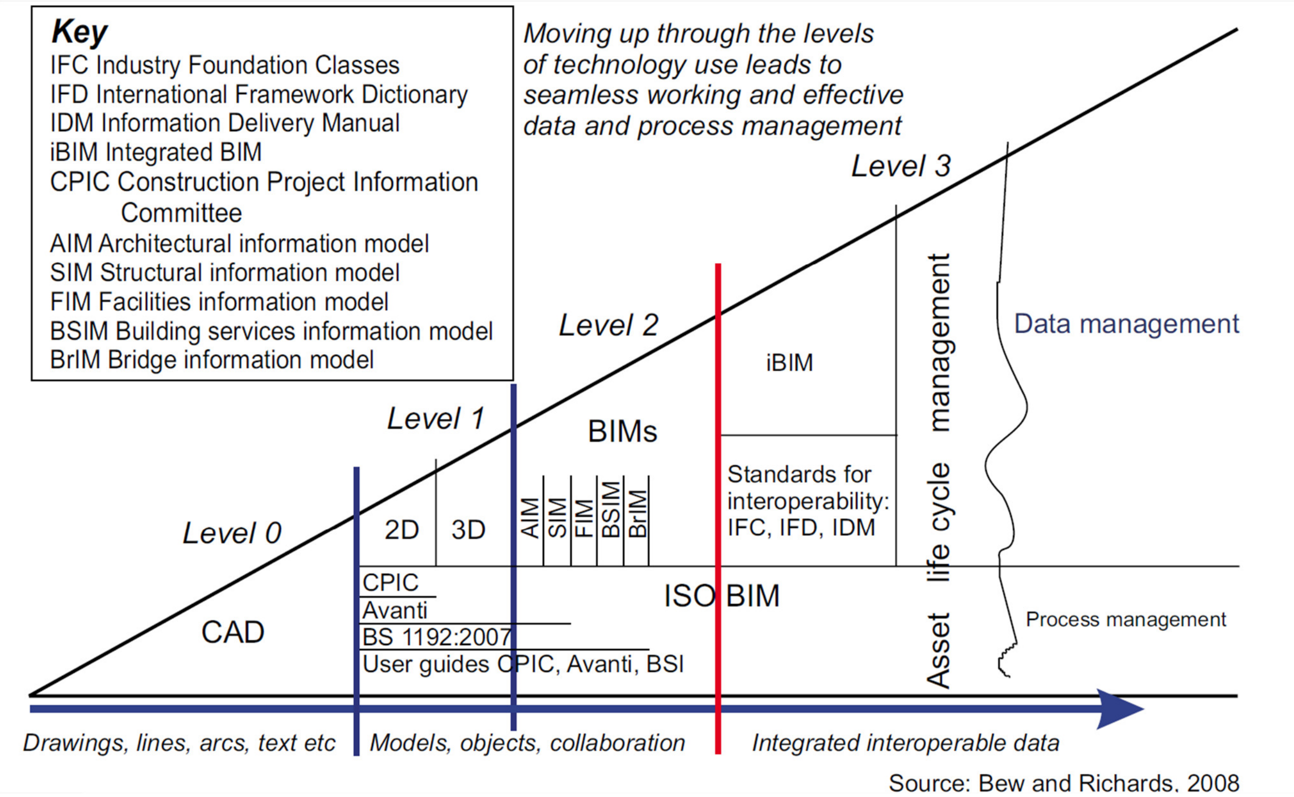

Figure 2.1: BIM Maturity Diagram (source: Bew and Richards 2008)

As mentioned previously, several versions of the BIM Maturity Diagram have been produced. For instance, the following:

- BIM Maturity diagrams (BIS, 2011) - One of these diagrams has further information about the standards, guidance, classifications, and delivery. The other one has information about the tools.
- BIM Maturity Model has also been translated for a specific market, for instance, Australia (CRC, 2009), Dutch BIM Levels (Bouw Informatie Raad, 2014).
- Another BIM Maturity Model diagram containing some key points of each BIM Level has been produced by (Rozmanith, 2014).

The concept of BIM levels has been broadly accepted as a way of recognisable criteria of what is required to be considered BIM-compliant. This approach offers a progressive, with specified and identifiable goals within levels ranging from 0 to 3. A brief description of each level is given below which is based on (NBS, 2014a, 2014b; The B1M Limited, 2014):

Level 0 BIM: At this level, there is no collaboration and only 2D CAD is utilised. The use of paper or electronic prints or a combination of both is common at this level. The majority of the industry has already moved up from this level (NBS, 2014b).

Level 1 BIM: At this level, a combination of 3D and 2D CAD is utilised. A significant number of organisations are at this level. There is no collaboration between different stakeholders, with each manages its own data.

Level 2 BIM: At this level, there is a collaboration between the stakeholders who use their own 3D CAD models. This is achieved by using a common file format for sharing design information which allows stakeholders to combine and check their data. For this to work, the CAD software used by the parties must have the capability to export to one of the common file formats.

Level 3 BIM: This fully integrated single project model held in a centralised repository allows collaboration between all stakeholders. This means, all relevant parties not only can access but also modify the same model. This is known as Open BIM compliant with IFC.

The three levels of BIM Maturity are different from the various dimensions of the building information data. For instance, the use of BIM data to analyse time is 4D, 5D is for cost management while 6D is for the Facilities Management (FM) purposes. All these elements could be found in Level 2 or Level 3 BIM (The B1M Limited, 2014).

It is important to note there is a lack of detailed documentation for Level 3 BIM concepts but some key aspects can still be mentioned based on Rozmanith (2014).

- The BIM Level 2 lacks an integrated system to leverage BIM data which results in builders and suppliers unable to fully collaborate on the model.
- The idea behind BIM Level 3 is to establish a single source of data stored in a database which provides integration preferably through a cloud-based web services solution.

The UK Government strategy paper (Cabinet Office, 2011) defined four maturity levels of BIM. These levels are based on both the level of technology used to design a building but also the level of collaboration within the process (Building, 2014a). As mentioned previously, in 2016 UK Government mandate to use Level 2 BIM on public-sector projects has come into force.

It is also worth mentioning here, some important points from the UK Government's Construction 2025 vision (HM Government, 2013).

- The UK Government and industry is expected to move to Level 3 BIM between 2016 and 2025.
- To deliver more sustainable buildings, quickly and efficiently, the implementation of BIM will be necessary. Also, for the successful implementation of a wider offsite manufacturing strategy, BIM is critical.

For more information about the UK BIM related standards, see (British Standards Institution, no date).

2.2.3.2 Support for BIM

BIM has strong backing from various governments particularly the UK who is one of the leaders in providing active support for BIM. The UK Government's Construction 2025 vision (HM Government, 2013) considers BIM as an integral part of its aspiration for UK Construction to achieve: 33% lower costs, 50% faster delivery, 50% improvement in exports and 50% lower emissions. This Construction 2025 vision report also forecasts that the global construction market will grow by over 70% by 2025 and in order to deliver more sustainable buildings, quickly and efficiently, implementation of BIM will be necessary.

The UK government's BIM mandate which was announced in the Government Construction Strategy document (Cabinet Office, 2011), required the use of Level 2 BIM on all public projects by 2016. As part of this strategy, a series of documents were produced to set out the requirements for achieving Level 2 BIM to facilitate its adoption in the UK (BSI, 2016).

In 2016, the EU BIM Task Group (EU BIM Task Group, 2016), a network supported by the European Commission, was founded. This now includes 23 countries in Europe. In December 2018, the EU BIM Task Group announced setting its roadmap for the coming years to direct the efforts towards the digitalisation of the construction sector at the European level.

The support for BIM in various countries around the world has been reported in a number of articles and reports (McAuley, Hore and West, 2017; Singh, 2017; Lorek, 2018; MEPcontent, 2018; Paul, 2018). Based on what has been reported, without going into details and covering all the countries, the following should provide an indication of the support for BIM in some of the countries: The UK is one of the leaders in support for BIM at the government level, in the United States some states have put BIM mandates in place, in Germany the use of BIM will be mandatory for all transportation projects by the end of 2020, Scandinavian countries are the early adopters of BIM and have public standards currently in place, and BIM is also mandated in France.

The current situation of BIM adoption can be found in the National BIM Report 2018 (NBS, 2018). One of the key findings mentioned in the report is that nearly three quarters of those surveyed are aware and using BIM, with only 1% unaware. Also, almost two thirds of the respondents, agree that the Government requires BIM on its projects, but a similar number do not feel that this is being enforced. In short, BIM usage has increased by 12% compared to the previous year. A somewhat similar situation has been reported in other surveys such as the Building's fifth annual BIM survey (Champ, 2018). The survey reported that the use of BIM has reached 73% and for Level 2 from 43% in 2017 to 48% in 2018.

The buildingSMART have included a categorised list (buildingSMART, 2019a), intended to be an official resource, of all software applications/utilities that support BIM (IFC import and/or export functionality). This list is maintained by buildingSMART in their IFC-Compatible Implementations Database. As of early 2019, 219 software applications/utilities have been listed in 12 categories (Architectural, Building Performance Energy Analysis and Simulation, Building Services, Construction Management, Data Server, Development Tools, Facility Management, General Modelling, Geographic Information System, Model Viewer, Other, and Structural).

A number of projects across the world utilising BIM have been reported (BIM Community, no date; BIM+, no date; GRAPHISOFT, no date; Arup, 2014). For instance, the following: Victoria station upgrade, Irina Viner-Usmanova Rhythmic Gymnastics Center in the Luzhniki Complex, Moscow, and Project OVE.

2.2.3.3 Current BIM limitations and issues

BIM is evolving and has gone through a significant improvement which has resulted in increased support by the professionals and BIM product vendors. However, several issues and limitations have been reported in various articles and surveys. For instance, Building's fifth annual BIM survey (Champ, 2018) has reported the following six commonly mentioned problems by the survey respondents: 1) Increased cost in the design phase, 2) Increased time spent in the design phase, 3)

Difficulties securing staff/other project team members with requisite expertise, 4) Difficulty managing additional volume/complexity of digital information, 5) Difficulty using the BIM model to aid in building's operational/FM phase, and 6) Poorer/more formulaic design.

In addition to these, other issues that have been reported are:

- Structural and BIM process issues, including model ownership, intellectual property, commercial confidentiality, and insurance models (Building, 2014a).
- IFC data exchange problems related to importing and exporting of IFC data between BIM tools (Cheng and Wu, 2013). A similar software compatibility issue using ArchiCAD (GRAPHISOFT, 2019a) and Revit (Autodesk, 2019) as examples was also reported by Svetel, Jarić and Budimir (2014).
- According to Svetel, Jarić and Budimir (2014), as far as the current level of BIM development is concerned, it is more suitable for large companies with teams of architects and engineers.
- BIM support is more focused on a specific actor (architect, structural engineer and building service engineer) and not yet on the features that give access to safety & security models and results, sharing design and structural data that will help a safe evacuation in case a hazard occurs (Janssen, Thomas and Joubert, 2013).

2.3 Fire Safety Engineering

Fire Safety Engineering (FSE) is "*an application of scientific and engineering principles to the protection of people, property and the environment from fire*" (BSI, 2002). It is worth pointing out here that Fire Engineering covers Fire Protection Engineering (focuses on fire detection, suppression and mitigation) as well as FSE (focuses on the evacuation of occupants by keeping a tenable environment and structure safety).

FSE is a relatively young but evolving safety support discipline which takes a wide range of data input from other disciplines and utilises fire, evacuation and structural modelling tools for analysing the fire safety aspects of a structure. This multi-disciplinary nature of the data (Architecture, Engineering, Physics, Computer Science, Chemistry, Psychology, Physiology, Economics, Mathematics and Statistics) makes FSE not only complex but also highly intercoupled with the other building information domains. The main contribution of FSE is at the initial building design phase but it is also utilised in case of change in building design/usage, structural and forensic analysis.

Fire safety in the built environment is of utmost importance and has the following objectives (ISO, 2018b): Safety of life, Property protection, Continuity of operations, Protection of the environment, and Preservation of heritage. The national regulations or building codes consider life safety and protection of the environment as an essential requirement (ISO, 2018b). To ensure these objectives are met, two fire safety design methods are used.

The first one is the Prescriptive method which uses a set of rules by focussing on the following two main aspects: a) Egress design rules in the geometric form, and limitations of escape routes (maximum length of routes, the width, choice, flow capacities and number of exits), and b) Fire protection rules in the form of fire protection zone, number of hours fire protection of the zones, fire extinguisher placement etc.

The second fire safety design method is Performance based which unlike the traditional Prescriptive approach, applies an engineering approach to achieve the fire safety objectives. The main idea is to find the safe maximum time limit for evacuation and assess if the structure can be reasonably evacuated within this time period. By utilising modelling and simulations, the performance-based approach attempts to establish whether the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET) plus a specified safety factor. The ASET is driven by the fire development and often determined by a fire simulation model while RSET is driven by human behaviour and often determined by an evacuation simulation model. The safety factor is a multiplicative or additive adjustment applied to the calculated values to compensate for uncertainty in methods, calculations, input data and assumptions (ISO, 2018b). This comparison between ASET and RSET is important because the performance-based life-safety design depends on it (Purser, 2003). It is important to mention here that the ASET calculation depends on the tenability which is multifaceted (e.g. temperature, thermal radiation, lower oxygen because of fire and toxic fire gases such as CO and CO_2). The tenability criteria can be described as "*the maximum exposure to hazards from a fire that can be tolerated without causing incapacitation*" (CFPA Europe, 2009). For tenability criteria guidelines, see (BSI, 2004). In addition to this approach, there is another advanced option where the ASET and RSET are coupled. For coupled analysis, the impact of fire hazards on the population is taken on board which can provide more realistic results (Galea *et al.*, 2008). This approach is beneficial as it allows for the quantification of tenability conditions (Rådemar *et al.*, 2018).

In terms of building regulations, Meacham (2017) has highlighted that in the last few decades there has been a shift in several countries from Prescriptive to Performance based approach due to a need for innovation in building design and materials by reducing regulatory requirements and minimising the cost of building regulation. However, these factors have resulted in issues such as competing objectives and failures within some building regulatory systems. To resolve these issues, the building regulatory systems should evolve. The following six steps, summarised here, have been mentioned by (Meacham, 2017) that needs to be taken in order to move forward:

1) View buildings and building regulatory systems as complex systems of systems with strong interrelationships between overall building performance and subsystems.
2) To meet the policy objectives, the input is required from a broader set of stakeholders.
3) The basis for performance requirements should be made common.
4) The changes need to be identified, evaluated and implemented in order to incorporate the new objectives.
5) To address the existing buildings, the future building regulatory systems should improve.
6) A new process for building regulation development would be useful.

2.3.1 Fire modelling

The use of fire modelling is mainly to predict the spread of smoke and heat from fires (BRE, no date). The following are the two general types of computer models for analysing enclosure fire development:

<u>Probabilistic</u>: Normally they do not directly use physical and chemical equations describing the fire processes and treat fire growth as a series of sequential events.

<u>Deterministic</u>: Based on physics and chemistry, interrelated mathematical expressions are used to represent the processes in a compartment fire (Walton and Budnick, 1997).

Mathematical fire models, based on their use and level of precision and complexity, can be divided into following three categories: Hand calculations, Zone models, and Computational Fluid Dynamics (CFD) or Field models (Gorbett, 2008).

Zone Models

Zone models are relatively simple models that divide a given space into zones where each zone is assumed to have uniform conditions. These zones are commonly known as the upper and lower zones or layers (Gorbett, 2008). The upper layer consists of heated combustion products while the lower layer is composed of cooler air (Putorti, no date).

Zone models use experimental information and they apply strong simplifications as well. The application of Zone models is limited to the geometry characteristics for which the model was tested and validated (Tavelli, Rota and Derudi, 2014). Also, the basic approach to the Zone model has been well studied and therefore the chances of developing a new Zone model are low (Olenick and Carpenter, 2003).

Field Models

Field models are also known as CFD models and are based on the physical principles of energy, mass, and momentum conservation (Putorti, no date; Gorbett, 2008). They divide an enclosure into a large number of small cells and calculate the movement of heat and smoke between them over time. At any point in time within each cell, it is possible to acquire temperature, velocity, and gas concentrations. Like Zone models, the properties throughout each cell are assumed to be constant in Field models. However, the conditions in the enclosure can be predicted in a much more accurate way due to the larger number of cells (Putorti, no date).

Field models are suitable for all types of spaces whether they are very large or very small including those with complex geometries. In complex multiple room configurations, Field models can accurately describe the fire phenomenon, unlike the Zone models. However, on the other hand, the Field models require detailed input information and more computing resources in order to model the fire which can have costly time delay implications in obtaining a solution. The use of CFD modelling is extensive in other engineering fields such as mechanical and aerospace which means the testing, development and verification of CFD codes by a large number of engineers is possible (Morente, Quintana and Wald, no date; Putorti, no date; Olenick and Carpenter, 2003).

For further description and use of various models including a comparison of their strengths and weaknesses, see (Tofiło, Węgrzyński and Porowski, 2016).

Fire modelling applications and review of fire and smoke models

There are many applications of computer fire models. These include design and analysis of fire protection systems, evaluation of the effects of fire on people and property, post fire reconstruction and fire risk assessment. They are widely used for design and evaluation of fire safety of buildings and facilities (Rein *et al.*, 2007; Gorbett, 2008).

The first informative survey of computer models for Fire and Smoke by Friedman (1992) identified 62 programs plus 12 additional models divided into various categories including Zone and Field models. This highly cited survey provided a list with some details of 31 Zone models and 10 Field models. In 2003, Olenick (2003) published an update to Friedman (1992) survey work and identified 168 computer modelling programs for fire and smoke divided into several categories. The updated survey by Olenick (2003) provided comprehensive information about the models unlike the basic details provided by Friedman (1992). The survey listed 48 Zone models (3 more but with no details) and 17 Field models (3 more but with no details). Further updates to this survey were provided in 2007, 2010, and 2013/2014, resulting in some new models as well as updated information for some already listed models (Olenick, 2015). Another review by Morente (no date) provided an update to Olenick (2003) and identified 177 software tools, 30 of them publicly available. Out of 177 tools, 49 were categorised as Zone models and 20 as Field models.

2.3.2 Evacuation modelling

Evacuation modelling *"is the development and application of predictive tools to describe the movement and behaviour of a population within a defined region of space in which the population and/or space are subjected to emergency and possibly worsening hazardous conditions."* (FSEG, 2013). The work on quantifying and modelling human movement and behaviour has seen progress over the decades and has taken the following two routes: 1) The movement of people under normal non-emergency conditions, 2) The movement of people under emergency conditions, e.g. evacuation of a building subjected to a fire threat (Gwynne *et al.*, 1999). The following two categories of models attempt to simulate evacuation: 1) referred to as Ball-bearing model which focuses only on the capacity of the structure and its various components. 2) Attempts to associate movement with behaviour (Gwynne *et al.*, 1999).

A discussion with a graphical illustration of the various types of models was provided by Gwynne *et al.* (1999). Considering the availability of a variety of modelling methodologies by which different categories of evacuation model can be represented, the review by Gwynne *et al.* (1999) provided valuable insight. The diagram produced by Gwynne *et al.* (1999) has been adapted as shown in Figure 2.2 by excluding the names of evacuation modelling tools.

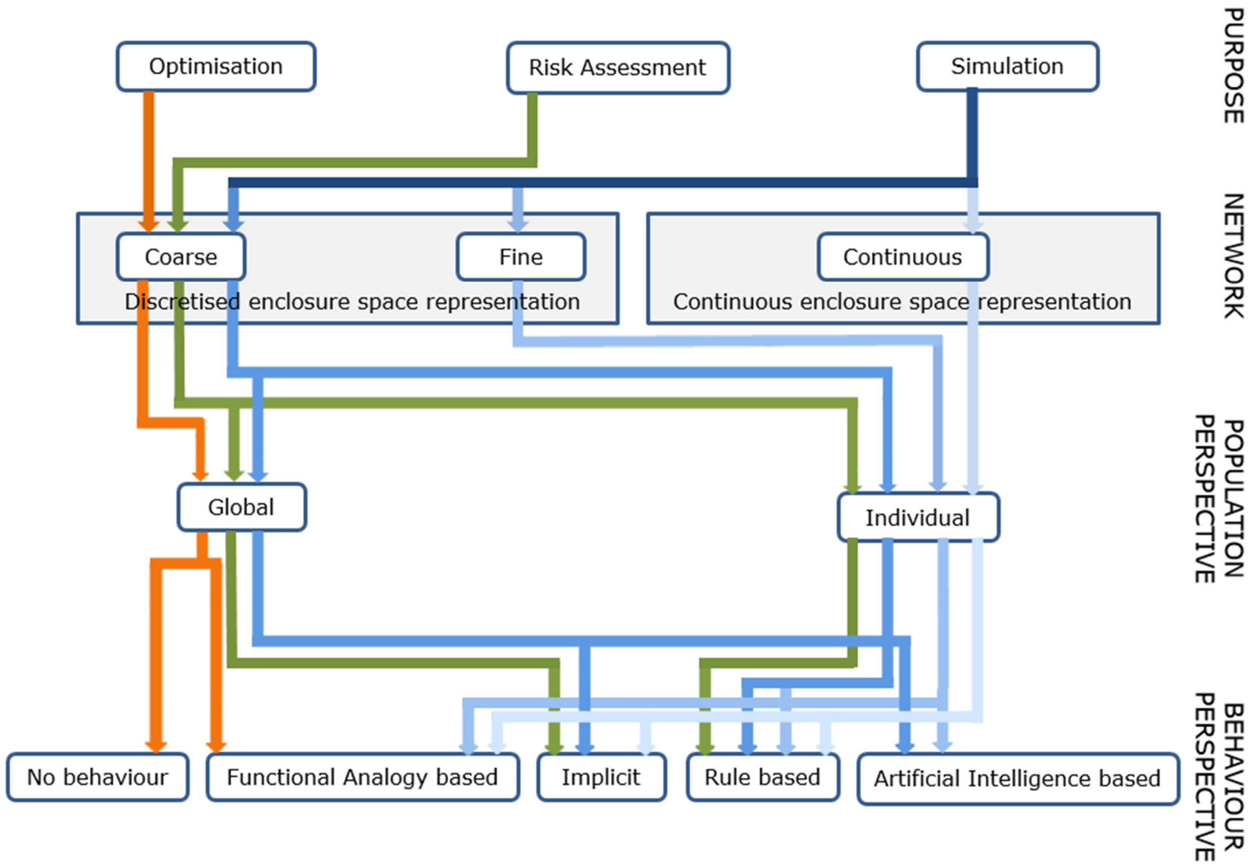

Figure 2.2: Evacuation Modelling Methodologies, adapted from (Gwynne *et al.*, 1999)

Only a brief description of model types shown in Figure 2.2 is mentioned here for the purpose of clarity as the details can be found in (Gwynne *et al.*, 1999; FSEG, 2013).

- Purpose
  - *Optimisation*: Based on the assumption that the occupants evacuate efficiently and take optimal evacuation paths.
  - *Simulation*: Attempts to realistically represent behaviour and movement observed in real evacuations including decisions made and paths taken.
  - *Risk assessment*: Attempts to identify hazards that are associated with evacuation due to a fire.
- Method used to present the enclosure

  - *Discretised:* Space is discretised into sub-regions each connected to neighbours.
    - *Coarse network:* The geometry is defined by partitions derived from structure, e.g. corridor or room.
    - *Fine network:* The entire floor space of the enclosure is usually covered in a collection of nodes.
  - *Continuous:* Entire space is available for occupation and movement.
- Population perspective adopted
  - *Individual:* Allows personal attributes to be assigned to the population.
  - *Global:* Do not recognise the individual agent (A person is called an agent in simulation).
- The behavioural perspective used
  - *No Behavioural Rules:* No behavioural rules applied.
  - *Functional Analogy Behaviour:* Based on a set of equations applied to the entire population that completely controls the population's response.
  - *Implicit Behaviour:* Behavioural rules not explicitly declared but assumed to be implicitly represented using complex physical methods.
  - *Rule Based Behavioural System:* The behavioural characteristics of individual occupants are explicitly recognised.
  - *Artificial Intelligence Based Behavioural System:* Individual occupants, with respect to their surrounding environment, are designed to represent human intelligence as much as possible.

Evacuation modelling aides in determining the evacuation performance of a population/enclosure subjected to a predefined hazardous environment and in assessing the level of safety afforded to the occupants by the layout and design of the enclosure. The people movement modelling can also be used for simulating non-emergency circulation situations. This can provide information about exit usage, population distribution, and congestion levels attained. There are a number of ways this can be of use, for instance, in commercial applications (e.g. airport terminals or shopping centres), procedural design, understanding the transition between non-emergency and emergency behaviour (FSEG, 2013). Evacuation modelling can also be applied to other types of structures as well such as aircrafts, rail systems, maritime, and cities (Kuligowski, Peacock and Hoskins, 2010; FSEG, 2013).

Several surveys/reviews of evacuation models have been conducted in the last few decades. These reviews include those that have particularly provided information related to the definition and characterisation of the evacuation model capabilities, for instance (Watts, 1987; Friedman, 1992; Gwynne *et al.*, 1999; Olenick and Carpenter, 2003; Santos and Aguirre, 2004; Kuligowski, Peacock and Hoskins, 2010). Other reviews such as Ronchi and Nilsson (2013) reviewed six main evacuation model, and Morente (no date) identified 25 evacuation models. The most recent of these reviews was by Kuligowski (2010) which provided a comprehensive review of 26 evacuation models. This review was also an update to the previous version (Kuligowski and Peacock, 2005) by the same authors. A further review of model capabilities for high-rise building evacuations was provided by Ronchi and Nilsson (2013) which compared nine models.

The above-mentioned reviews have provided an insight into a growing area of fire and evacuation modelling where a significant number of variations in terms of capabilities of the reviewed tools exist. However, there is a lack of reviews that cover the capabilities of fire and evacuation modelling tools in relation to their level of support for BIM.

2.3.3 Data sharing between fire and evacuation modelling tools

In this section, the following points are covered: input of fire data in evacuation modelling tools, and input of evacuation data in fire modelling tools.

2.3.3.1 Input of fire data in evacuation modelling tools

A number of evacuation modelling tools support the use of fire data to understand population exposure to fire effluents in evacuation simulations (Kuligowski, Peacock and Hoskins, 2010). This is achieved in the following ways: (1) Importing fire data/results from a fire model, (2) allowing the user to input fire data at certain times during evacuation, or (3) the model may have its own fire model that can be run simultaneously with the evacuation model. Those evacuation tools that cannot include fire data, run simulations in a non-fire mode which is basically similar to a fire drill (Kuligowski, Peacock and Hoskins, 2010). The review by (Kuligowski, Peacock and Hoskins, 2010), identified 14 out of 26 models that have some level of support to incorporate fire data into simulations. However, out of these 14 models, 7 (5 publicly available but some only on a consultancy basis) allow import from a fire model while only 2 (1 publicly available) have their own simultaneous fire model.

2.3.3.2 Input of evacuation data in fire modelling tools

In terms of fire modelling tools supporting the use of evacuation data, the situation is quite different. This is because the current evacuation models do not allow population actions to impact fire evolution. This is primarily due to practical issues associated with the differences in computational costs between evacuation and fire models. However, two-way coupling capabilities where building occupants can interact with the evolution of the simulated fire development are currently being developed by the Fire Safety Engineering Group (FSEG). The nature of this interaction allows occupants to open or close doors thereby changing fire compartmentation and/or impacting stair pressurisation, firefighting and/or smoke management.

2.4 Data sharing between BIM and fire and evacuation Modelling tools

The AEC industry consists of many contributing disciplines (e.g. Architecture and Engineering) that create specific project deliverables. Therefore, multiple exchanges between people, disciplines, and project phases are required (Autodesk, 2013). In short, several sub-models of the same building project are created usually using different software tools to capture different aspects of design. Figure 2.3 (Autodesk, 2013) provides an example of various data formats used on a typical building project.

Project Data	File Type
Architectural Model	IFC, RVT, DWG, DGN, PLN, NWD
Structural Model	IFC,CIS/2
CAD Data	DXF,DWG
GIS Data	SHP,KMZ,WFS,GML
Civil Engineering	LandXML, DWG, DGN
Cost Estimating	XLSX,ODBC
Visualisation Models	FBX,SKP,NWD
COBie Data	IFC,XLSX
Scheduling Data	P3,MPP
Energy Analysis	IFC,gbXML
Site Imagery	JPG,PNG

Figure 2.3: Example of data formats used on a building project (Autodesk, 2013)

Some of the file formats shown in Figure 2.3, such as IFC have already been discussed. Furthermore, the data exchange between fire and evacuation modelling tools has been covered as well.

The IFC Model implements many of the features (e.g. object-orientation and association of attributes with objects) that are required for integration with fire simulation software. The data exchange formats such as DXF are unable to provide a rich description of buildings as they are limited to basic geometry. Based on this, Spearpoint (2005) reviewed Fire Engineering related entities and properties in IFC 2x2 and examined how they can be mapped to the input requirements of the Zone model BRANZFIRE fire simulation software. Further work was then undertaken by Spearpoint (2007) and Dimyadi (2007).

As the above review was for an older version of IFC i.e. 2x2, the author conducted a further review of IFC 2x3 and IFC4 for FSE relevant data support as part of this study and it is included in Appendix A.

2.4.1 Input of BIM data in evacuation and fire modelling tools

Some earlier work on extracting BIM data from an IFC file was demonstrated by Spearpoint (2007). It was achieved by transferring of IFC v2x2 building data between a CAD program and the BRANZFIRE fire modelling tool. Also, Dimyadi, Spearpoint and Amor (2007) developed a conversion tool for CFD based fire modelling tool Fire Dynamics Simulator (FDS) (McGrattan and Forney, 2004), in combination with a revised version of Fire Engineering IFC Model parser introduced by Spearpoint (2007). This tool converted building geometries from a BIM design tool to generate the corresponding FDS input data.

Current support for BIM data in evacuation modelling tools

Currently, the support for BIM data in evacuation modelling tools is significantly limited and mainly restricted to extraction of geometry data such as walls and doors. An initial review by the author identified only 3 evacuation modelling tools that support BIM data import but since then the number has increased. Based on the recent review by the author, the evacuation modelling tools listed in Table 2.2 have support for IFC file import for geometry extraction. Also, included in Table 2.2 is an indication of the data output file format for the generated simulation data.

Table 2.2: Evacuation modelling tools supporting BIM IFC file import

	Evacuation modelling tool	Vendor	Support for fire data	Output file format
1	buildingEXODUS	FSEG	Yes	SIM
2	LEGION	Bentley	Yes	RES
3	MassMotion	Oasys Software Limited (a subsidiary of Arup)	No	MMDB (SQLite database file)
4	Pathfinder	Thunderhead Engineering	Yes	CSV
5	Pedestrian Dynamics	INCONTROL	No	Not specified
6	STEPS	Mott MacDonald	Yes	CSV, XLSX

The following is a further description of the information shown in Table 2.2:

1) <u>buildingEXODUS:</u> The IFC import option in buildingEXODUS allows users to not only select the floor they want to import but also the objects it contains (e.g. beams, doors and walls). In terms of fire hazards, the buildingEXODUS has support for smoke, heat, irritant and toxic gases. The fire hazard data generated by CFAST Zone model (Peacock, Reneke and Forney, 2018) and SMARTFIRE CFD model (Ewer *et al.*, 2013) can be loaded as a data file (.DAT) in buildingEXODUS (Galea, Lawrence, *et al.*, 2017).

2) <u>LEGION</u>: LEGION software consists of LEGION Model Builder and LEGION Simulator. These two tools work together to enable users to simulate pedestrian movement within a defined space. The geometry data imported from an IFC file is translated into 2D CAD for use in LEGION Model Builder because it is a 2D programme. During the import process, the user can decide to include or exclude certain elements such as slabs, walls, windows, columns, doors and openings. In terms of importing fire hazard data, LEGION can use the output data such as temperature, visibility and toxicity from FDS (Legion, 2019).

3) MassMotion: In MassMotion, geometry elements in an IFC file are imported to automatically generate corresponding MassMotion objects (e.g. Space, Escalator, Door, Stair, Furnishing Element and Ramp) (Oasys, 2017). Currently, there is no support for importing fire hazard data in MassMotion.

4) Pathfinder: The latest release 2018.4 of Pathfinder has the capability to import IFC files. In Pathfinder, this feature allows automatic extraction of floors, doors, and stairs (Thunderhead Engineering, 2018a). It has an option to import smoke and fire data generated by FDS and by utilising that, Pathfinder can demonstrate areas of high danger by tracking occupant Fractional Effective Dose (FED) of contaminants. This information is exported to a CSV file.

5) Pedestrian Dynamics: There is support for geometry extraction from an IFC file in Pedestrian Dynamics (INCONTROL, 2016). However, no further description of the IFC import feature and no indication of the simulation generated output data export file format is provided.

6) STEPS: STEPS provides a 3D modelling environment and uses xBIM library (xBIM, 2019) to import geometry from a BIM IFC file to automatically create circulation area, exits, blockages and basic stairs. It can import smoke data from various CFD packages, such as FDS, CFX, Fluent, and CFAST. Also, by importing smoke data from CFX or FDS, STEPS can calculate the total accumulated exposure dose data for any toxic element (Mott MacDonald, 2016).

See Table B1 in Appendix B for further information about the type and level of support in some selected evacuation modelling tools in terms of evacuation data.

Current support for BIM data in fire modelling tools

Currently, the fire modelling tools have very limited support for importing data from BIM. An initial review identified no publicly available fire modelling tool that supports BIM data import but since then support has been added in some tools. Based on the recent review by the author, the fire modelling tools listed in Table 2.3 have support for IFC file import for geometry extraction. An indication of the data output file format for the generated simulation data is also included in Table 2.3.

Table 2.3: Fire modelling tools supporting BIM IFC file import

	Fire modelling tool	Vendor	Output fire hazard data file format
1	PyroSim	Thunderhead Engineering	CSV
2	SMARTFIRE	FSEG	VTU, DAT

1) PyroSim: PyroSim is a Graphical User Interface (GUI) for FDS. The latest release v2018.3.1210 of PyroSim (Thunderhead Engineering, 2018c) has the capability to import IFC files and extract geometry. It should be noted that according to Diettes (2019), PyroSim can also import the material names and create surfaces with those names. However, material properties are not imported.

2) SMARTFIRE: The development work on importing an IFC file in SMARTFIRE is, at the time of writing, a work in progress. However, for now, a command line application has been developed that can read an IFC file. Currently, this option is only available for internal research purpose, but it will be part of the next public release.

See Table B2 in Appendix B for further information about the type of support for fire hazard data in fire modelling tools SMARTFIRE and PyroSim.

2.4.2 Data output from evacuation and fire modelling tools for BIM

Currently, even though a reasonable level of support in BIM exists for the input data required for FSE, there is no explicit provision for the fire and evacuation modelling generated essential safety analysis output data. However, it is important to mention here that despite this lack of explicit support, some BIM packages such as Revit do provide options to add custom data sets to any element.

The data sharing between BIM and FSE using fire and evacuation tools is relatively at an earlier stage. The facility to export or write data back to BIM from fire and evacuation modelling tools is currently not available.

2.4.3 Review of related research studies

Several research studies have been undertaken on BIM with some aspect of fire safety. For instance, the following:

- Dimyadi, Solihin and Amor (2018) examined two comparative approaches to provide data from an IFC file as input for the FDS fire modelling tool. The first approach mentioned is called BIM Rule Language (BIMRL) which has been developed as a module to provide an efficient way to query the BIM data by transforming IFC model into a Relational Database Management Systems (RDBMS) simplified schema (Solihin *et al.*, 2017). The BIMRL approach was compared with the Blender 3D modelling application (Brito, 2008) with third-party software add-ons. The conclusion of this study was that BIMRL is a better approach due to its flexibility. Also, potentially it can be integrated with automated compliance audit framework that can be interfaced with FDS.
- Dimyadi, Amor and Spearpoint (2016) presented a process of exchanging BIM and Regulatory Knowledge Model (RKM) which was proposed by the same author in a previous study (Dimyadi *et al.*, 2014) data with the EvacuatioNZ, a risk-based fire evacuation simulation tool, for compliance audit within the New Zealand regulatory environment context. The conclusion of this study was that considerable time can be saved if the input data required for simulation can be automatically extracted from BIM. The study also suggested that further investigation is needed to identify the scope of fire safety data needed to enable sharing of BIM data with various other types of fire simulations.
- Mayer *et al*. (2014) presented their work on the development of a pedestrian simulation tool to work with BIM. The main part of the presented work was the BIM IFC geometry data import into the pedestrian simulation tool.
- Wang *et al*. (2014) developed a BIM-based virtual environment for improving building emergency management by utilising BIM to work with virtual reality technologies to provide real-time fire evacuation guidance. The study demonstrated a real-time two-way information flow between the virtual environment and a real building user. However, the BIM based virtual environment worked with Revit API and a specific data format to transfer building information and not the standard IFC format.

All these studies have provided valuable insights into BIM with fire safety related data sharing aspects. However, a more holistic view of FSE with BIM is needed. To achieve that, first, a strategy is needed to cater for various aspects of BIM with enhancements to the IFC Model from the FSE perspective. The input and output data requirements for FSE and how BIM can support that is needed in order to provide a solid base for future development. Also, how the existing FSE data sharing approach can be improved to work within the BIM context requires consideration.

Without resolving these key issues any future development including automation will not be able to realise the full benefits of BIM with FSE.

2.5 Smart Buildings

Smart Buildings are also called Intelligent Buildings (Ehrlich and Goldschmidt, 2008) and in this chapter, Smart/Intelligent are used interchangeably in the context of buildings.

Many definitions of Intelligent Buildings have been suggested during the last two decades but no single definition is accepted worldwide because of the changing expectations due to the developments in information technology (Wang, 2010). The following is one of the high-level definitions:

"Use of technology and process to create a sustainable building that is safer and more productive for its occupants and more operationally efficient for its owners"(Ehrlich and Goldschmidt, 2008).

The concept of Intelligent/Smart Building has been around since the 80s. A more detailed background to Intelligent buildings is provided by (Himanen, 2003; Wang, 2010) but a brief description is presented here for the purpose of clarity. The earlier progress and potential future trends were best captured by the Intelligent Building Pyramid which was introduced in 1992 by European Intelligent Building Group EIBG, focused on the communication technology and the integration of building control and monitoring systems. This pyramid was further updated by DEGW in 1999 by adding remote control and the mobile technology to computer integrated building description (Himanen, 2003). In another modified and updated version of the Intelligent Building Pyramid (Wang, 2010), the pyramid was left open at the top to emphasize that the Intelligent Building systems are not enclosed within buildings but instead are joined with similar systems in other buildings and also to other information systems through the Internet.

First, before moving any further, it is essential to provide here some clarification of various commonly used terms within the context of Smart Buildings. These are Building Automation and Control Systems (BACS), Building Control System (BCS), Building Management System (BMS), and Building Automation System (BAS) that generally understood to refer to more or less the same systems (KMC Controls Inc, no date). A Smart Building is equipped with a data rich system, usually referred to by one of the above-mentioned terms. A BMS/BAS is a computer-based control system consists of both software and hardware which is installed in a building to control and monitor mainly Mechanical, Electrical, and Plumbing (MEP) systems. A Heating, Ventilation and Air-conditioning (HVAC) system is usually controlled and includes control of equipment such as chillers and boilers. Other systems that are often monitored and controlled using a BAS/BMS are Lighting, Power, Security, Fire alarm system, Elevators/escalators, etc.

According to Tang (2012), at their most basic form, Smart Buildings are *"buildings which are controlled by a computerised network of electronic sensors and controls to monitor and operate certain building functions such as mechanical and lighting systems"*. BAS provides links between sensors and controllers which could be located on several floors to a master controller. To support this, a front-end server and a back-end database are utilised.

A more detailed approach to differentiate Intelligent Buildings with normal buildings was provided by Ehrlich and Goldschmidt (2008) using a diagram called Intelligent Building Model The Intelligent Building Model diagram identified three levels, which for the purpose of clarity are briefly mentioned here based on the more detailed description by Ehrlich and Goldschmidt (2008).

1. *Building Systems*: This is the first or bottom level of the Intelligent Building Model and includes building system controls. The purpose of these controls is to provide the data needed for efficient operations.

2. *Systems Integration*: This is the second or middle level of the Intelligent Building Model. At this level, middleware is used that allows various systems to be interconnected by utilising protocols.

3. *Enterprise*: This is the third or top level of the Intelligent Building Model. At this level, Enterprise Management is achieved that can provide connections between the building systems and business systems. For managing groups of buildings as one enterprise, tools are also provided.

A simple representation of the three level structure was produced by Iwayemi (2012) while Kastner (2005) produced a hierarchically ordered three level structure for building automation systems. Based on IDC Technologies (2014), the three level structure is briefly mentioned below:

The Field Level: At this level, measuring environmental data and physical control of environment parameters is achieved.

Automation Level: At this level, automatic control of the data is performed.

Management System Level: At this level, global configuration and management tasks are realised.

For a more detailed description of the three levels, see (Kastner *et al.*, 2005; Granzer, Kastner and Reinisch, 2008; Iwayemi, Wan and Zhou, 2012). The five parts article series called 'Defining a Smart Building' (Sinopoli and Sharif, 2014c, 2014e, 2014d, 2014b, 2014a) highlighted a number of important points. The article series mentioned seventeen attributes in order to provide a common perspective/framework of a Smart Building. It pointed out that with the passage of time there will be further developments and therefore a possibility of additional attributes is expected. The seventeen major attributes of a Smart Building are: 1) Cabling infrastructure, 2) Lighting control systems, 3) Facility management tools, 4) System integration, 5) Audio-visual systems, 6) Plumbing and water, 7) Fire Alarm, 8) Occupant Satisfaction, 9) Network and Security, 10) Electrical, 11) Video Surveillance Systems, 12) Analytics, 13) Advanced Building Management System, 14) Communication and data infrastructure, 15) HVAC, 16) Access Control System, and 17) Sustainability and innovation.

It is also worth mentioning that Smart Buildings and Green buildings have many aspects which are similar but they are not identical concepts (Probst, 2013). Some of these commonalities are Optimise Energy Performance and Innovation in design which is captured in a diagram by Frost and Sullivan (2008).

2.5.1 Benefits

In Table 2.4, commonly mentioned benefits of Smart Buildings are listed mainly based on the following: (Ehrlich and Goldschmidt, 2008; Tang, 2012; Designing Buildings Wiki, 2015).

Table 2.4: Benefits of Smart Buildings

	Benefit	**Description**
1	Cost effective	Provides a built environment which is cost-effective by optimising the following four of its basic components and the relationships between them: structure, systems, services and management.
2	Integrated systems	Provides a common platform for different systems to communicate with each other.
3	Improved operational efficiency	Provides a comfortable and secure environment for users by delivering information through a combination of wired and wireless IT services.
4	Increased productivity and comfort	Based on the information provided by sensors and how they are programmed, various actions can be taken. For example, buildings can be pre-heated before their occupants arrive.
5	Actionable information	Provides building managers with building management systems to help them in optimising building performance by understanding and controlling their operation.
6	Data analytics	A large amount of data is generated by various subsystems in a Smart Building and often a facility is provided using a dashboard to analyse it even though it can be limited.

2.5.2 Data exchange/sharing approaches and standards for Smart Buildings

The control devices/servers communicate with end devices through protocols, to monitor, manage and provide services. This communication through protocols is implemented by hardware, software or both. By using cables or wireless transmitters/receivers, devices can be connected (Sinopoli, 2010).

The ISO's development of the Open System Interconnection (OSI) model is at the forefront of the growth of open network standards (Sinopoli, 2010). That is why, whenever there is a discussion on data communication, this 7 layers theoretical base Model is mentioned along with Transport Control Protocol/Internet Protocol (TCP/IP) Model which is a four layer practical base model developed by DARPA (Defense Advanced Research Projects Agency). It should be noted that building automation systems (e.g. HVAC, lighting and access control) exchange information with other devices using communication protocols but these are not always the same and therefore further integration is required. In a Smart Building, various systems are integrated from a physical and logical perspective. According to Ferreira *et al.* (2010), the following are three ways of achieving that:

- A complete solution is provided by the manufacturer using a proprietary communication protocol.
- By establishing a link between an open communication protocol and manufacturers.
- By using open standards protocols for different subsystems.

For BIM, the buildingSMART which is an international not-for-profit organisation is a worldwide authority for the creation and adoption of open international standards. The situation of Smart Buildings is different as there is no single, neutral, international organisation controlling the overall standards. This is because to achieve interoperability between the connected devices and systems within a building, a collaboration between various parties is required which is not easy considering they may be business competitors. However, voluntary collaboration over the years has led to the development and adoption of some open standards/protocols (Institute for building efficiency, 2011).

As mentioned previously, the system functionality of a BAS is broken up into three levels (Field level, Automation level, and Management level). There are many different protocols for BAS, and they can be used at one or all three of these levels. According to Granzer, Kastner and Reinisch

(2008), the three most recognised and used protocols are BACnet, LonWorks and KNX which can be used at all three levels, are application-independent and open standards. On the other hand, there are standards which are specifically used at a single level and can be for a specific application (e.g., the Digital Addressable Lighting Interface i.e. DALI) or have specific characteristics.

For data telecommunications, Ethernet and IP have been standards for years. BASs have specific industry protocols but they also have or are moving to convert or interface the protocols to IP (Sinopoli, 2010).

The following is a description of some widely used open standard protocols in Smart Building systems:

BACnet: Building Automation and Control Network (BACnet) is a data communication protocol for building automation and control networks. It was developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). BACnet is an ISO standard as well as a national standard in several countries including America (BACnet, no date).

BACnet specification was published and became ANSI/ASHRAE 135-1995 standard in 1995 with further revisions and upgrades followed over the next few years. In 2003, BACnet became an international standard ISO-16484-5 (BACnet, no date). BACnet International is an organisation to provide support for BACnet through interoperability and promotional activities (BACnet International, no date). Furthermore, another organisation called BACnet Testing Labs is responsible for BACnet products verification and lists products that have been tested to verify that they have correctly implemented BACnet (Sullivan, 2013b). According to Ferreira *et al.* (2010), BACnet is the most flexible solution for BAS in building offices environment. BACnet can be utilised in various types of systems available in buildings such as HVAC, lighting, life safety and access control (Piper, 2007).

LonWorks: It was created by the Echelon Corporation and in 1999 LonWorks became a standard for control networking (ANSI/CEA-709.1-B). It also became an international standard ISO/IEC 14908 in 2009. A protocol called LonTalk is responsible for handling communication between various devices while LonWorks is focused on defining information content and structure (Piper, 2007).

LonMark International which is supported by various manufacturers and end-users is an independent organisation for certifying LonWorks products (Sullivan, 2013b). LonWorks protocol is mainly used for building and home automation (Sinopoli, 2016) and widely deployed with hundreds of LonMark certified products available in the market (Siemens Building Technologies, 2014). In 2014, Echelon Corporation along with ConnectEx, Inc., announced the availability of BACnet over LonWorks as part of their IzoT (Industrial Internet of Things) platform for allowing interoperability between previously rival protocols (Echelon Corporation, no date).

Modbus: It is a communications protocol introduced by Modicon in 1979 and now owned by Schneider Electric. The initial focus of Modbus was on the communication to Programmable Logic Controllers (PLCs) manufactured by Modicon and used in industrial automation. In 2004, the Modbus standard was transferred to a non-profit organisation, Modbus-IDA (Sinopoli, 2016). The use of Modbus spread to other areas such as building automation, transportation, and energy applications due to its minimum hardware requirements, openness and simplicity (Piper, 2007).

KNX: It is a European (CENELEC EN 50090 and CEN EN 13321-1) and an International standard (ISO/IEC 14543-3) which is used for applications in home and building control, e.g. lighting and shutter control, HVAC, alarming and energy management. KNX merged the following three deprecated standards: European Home Systems Protocol (EHS), BatiBUS, and the European Installation Bus (EIB or Instabus) (San-Salvador and Herrero, 2012).

An Engineering Tool Software (ETS) which is a vendor-independent tool (ETS) is available for commissioning BASs based on KNX. Also, for communication between the devices, KNX can use data transmission networks in association with IP (Siemens Building Technologies, 2014).

OBIX: Open Building Information Xchange (oBIX) was initiated in 2003 as the Continental Automated Buildings Association (CABA) XML/Web Services Guideline Committee. The oBIX specification utilises web services for the exchange of information with the mechanical and electrical systems in buildings. oBIX is a technical committee at the Organisation for the Advancement of Structured Information Standards (OASIS) which is an international and non-profit consortium (OASIS, no date). One way of describing oBIX is the following: *"Open – all technical details freely available, Building – any and all building systems, Information – pertinent system data, and eXchange – interoperability"* (Considine, 2005).

Some observations

All building automation protocols have strengths and weaknesses, but some are more widely used. According to Piper (2007), three of the most widely used interoperability protocols BACnet, LonWorks and Modbus have vastly different approaches to interoperability. However, these differences do not necessarily mean that one protocol is better than the other. Davis (2011) does not believe that any single protocol is the secret to success in a building. In other words, no single protocol is best suited for every application (Sullivan, 2013a) and it is about choosing the right protocol for the right part of a building. For instance, Ferreira *et al.* (2010) performed a comparison between BACnet, LonWorks and KNX and concluded that KNX is the better solution for automation in homes while BACnet for offices. It should be noted that well established protocols (e.g. BACnet, LonTalk and Modbus) can be used over TCP/IP networks but they encounter several problems with security, routers, firewalls, and compatibility with other applications. This adds another challenge in an industry which is already dealing with several mostly incompatible protocols. As far as oBIX is concerned, by using web services technology, systems developed by different manufacturers which may be on different operating platforms, can be integrated with relative ease (Perumal *et al.*, 2010).

2.5.3 Current situation, limitations and future trends

Several regular reports have been produced by various companies (e.g. BSRIA, Frost & Sullivan, Memoori and MarketsandMarkets) regarding current Smart Building market. Most of these reports are not freely available but a sample of findings have been provided. The vision, approach and solution provided by different vendors for Smart Building systems vary and a detailed comparison itself requires a separate study but according to Towler (2014), examples of leading companies are IBM, Siemens, Schneider Electric, and Honeywell with Microsoft and Google as potential leaders.

Limitations

Although there have been improvements, overall the legacy BMSs have the following shortcomings: limited integration capabilities, inadequate analytic tools and proprietary programming languages (Sinopoli, 2012). Integrated Building Automation solutions are still rare because of the problems with the installation and maintenance of different applications, such as security relevant applications. The process of installation and maintenance of different applications is not standardised and therefore changing the setup of a linked automation subsystem would likely to create another accreditation scenario (Veichtlbauer, Pfeiffenberger and Schrittesser, 2012). Even though communication protocol standards such as LonWorks and BACnet are available, the focus of BMS vendors is on developing rule-based systems which do not support self-adapting model based systems (Grzybek, Gulliver and Huang, 2010).

Future trends

Several market analyses reports have been produced forecasting the direction Smart Building industry is expected to take. Some of the future trends are mentioned below:

According to MarketsandMarkets (2016), the global Smart Building market is expected to grow from USD 5.71 Billion in 2016 to USD 31.74 Billion by 2022. Also, during the period 2017-2022, the Compound Annual Growth Rate (CAGR) is projected to be 33.7%.

The report called *'The Internet of Things in Smart Buildings 2014 to 2020'* by Memoori Business Intelligence Ltd (Memoori, 2014) made an assessment of the market for Internet of Things (IoT) Technologies, Networks and Services in Buildings for 2014 to 2020. This report mentioned Building Internet of Things (BIoT) and defined it as *"The overlaying of an IP network, connecting all the building services monitoring, analysing and controlling without the intervention of humans"*. It also highlighted the value of BIoT both in data and devices. The report then suggested that for providing better operational efficiency, the building equipment manufacturers must focus on systems that collect, store and analyse data in the cloud. The three largest segments represented in the report were Physical Security, Lighting Control, and Fire Detection and Safety. It forecasts that the overall market for systems in buildings will grow from \$110.9Bn in 2014 to \$181.1Bn in 2020. Also, the global market for the BIoT is expected to rise from \$22.93Bn in 2014 to over \$85Bn in 2020.

Finally, another report (Memoori Business Intelligence Ltd, 2018) has made an objective assessment for Big Data in Smart Buildings market for 2018 to 2023 focusing primarily on software and professional services solutions. It forecasts growth for the total global market for Big Data in Smart Commercial buildings which could rise from \$15.6Bn at the end of 2018 to \$35.8Bn by 2023.

2.5.4 Support for Smart Building systems in BIM

The Building Automation Modelling (or Management) Information Exchange (BAMie) has been developed for automation and control systems. BAMie not only is a repository for data in automation and control systems, but it can provide a way to exchange data with other systems and people involved in the design, construction and operation of the building (Sinopoli, 2013).

BAMie is represented in the IFC Model by the Building Controls Domain i.e. *IfcBuildingControlsDomain* schema which is part of the Domain Layer. The concepts of building automation, control, instrumentation, and alarm are defined in the Building Controls Domain. The *IfcBuildingControlsDomain* schema provides support for actuator, alarm, controller, sensor, flow instrument, unitary control element. It also extends the concepts related to building services outlined in the *IfcSharedBldgServicesElements* schema (buildingSMART, 2013).

The *IfcBuildingControlsDomain* schema of the IFC Model provides both the physical representation as well as the placement information of building automation systems but it does not specify building automation protocols. However, mapping to standard protocols or vendor implementations is possible. The range of values (or associated units) is not specified by BAMie but the IFC representation for addressing using various protocols such as the oBIX, LonWorks, and BACnet is covered (East and Bogen, 2015). Furthermore, there is also an *IfcPerformanceHistory* entity which is used for capturing a real-time device state of control elements. The idea is to document actual performance over time that includes both the machine measured data from building automation systems and also human specified data representing the actual condition, predictions or simulations (buildingSMART, 2016b). See Appendix A has further information about the *IfcBuildingControlsDomain* schema.

There is very limited information available on the use of BIM with automation systems. Also, the use of BIM in FM is at an initial stage (Ebbesen, 2015; Benndorf, Wystrcil and Réhault, 2018).

2.6 Concluding remarks

An extensive literature review was conducted in this chapter covering mainly BIM and FSE but additionally Smart Buildings as well, focusing on the data sharing aspects. Based on the literature review the following conclusions have been made:

- **For BIM**
  - It is a digital data flow approach which is relatively new for the AEC industry, but its use is growing.
  - It has strong support from various governments such as the UK, and by the vendors. It also benefits from by having a not for profit and non-proprietary organisation buildingSMART defining and promoting open standards.
  - The goal is to reach Level 3 BIM, or beyond which is about data integration but that will take time. Currently, the industry is trying to move to Level 2 which is about collaboration.
  - It is safe to conclude that BIM will continue to evolve with increasing support from the AEC industry.
- **For FSE**
  - It is multi-disciplinary, complex and does not have its own domain specific sub-model unlike the Architectural model, Structural model, and others. This is maybe because FSE does not create a building's physical elements but instead uses mainly the Architectural model for the analysis of fire safety aspects. However, there are clear benefits in adding a fire safety layer on top of the Architectural model which can be called 'Fire safety analysis Layer' or even 'Fire safety analysis sub-model'. Some of the benefits that this layer or sub-model can offer by sharing a building's key fire safety aspects are a comparison of fire scenarios in terms of overall safety, ASET and RSET values, and performance of exits. Sharing of this information with the stakeholders will provide them with clarification and allow them to make decisions in a focused and quick way.
  - Several fire and evacuation modelling tools are available in the market but unlike BIM, there is no single independent organisation controlling standards. This means there is no one standard data exchange format for sharing simulations generated data between various tools.
- **Data sharing between BIM and FSE**
  - There is currently a lack of coherent strategy to fully utilise the benefits of FSE with BIM combination. For instance, sharing of fire safety analysis data using the fire and evacuation modelling tools with BIM is currently not supported. Furthermore, no BIM-based building design tool has data export facilitates which are intended for consumption by FSE based analysis tools. On the other hand, in

fire and evacuation modelling tools, the support for BIM is significantly limited and restricted to geometry extraction. A more holistic approach is needed to fully realise the potential benefits of FSE with BIM integration by resolving the current deficiencies.

- **Smart Buildings and support in BIM**
  - The Smart Building systems do have various proprietary or open standards for data communication promoted through vendors or standards organisations. These communication protocols are often in competition with each other with a varying level of market share. Unlike BIM, where IFC is the standard data model supported by a neutral organisation buildingSMART, the situation of Smart Building systems is different.
  - Support for building automation and control systems is available in BIM through an information exchange called BAMie which is represented in the IFC Model by the Building Controls Domain schema. However, the usage is currently at an early stage as it requires implementation support from the vendors. Nevertheless, this is an area which is expected to grow in the future.
- **Use of BIM with FSE combination in a Smart Building environment**
  - Without resolving the current deficiencies in BIM for FSE support and vice versa, the real benefits of BIM with FSE combination in a Smart Building environment cannot be realised fully. There are potential benefits of BIM with FSE combination that can be utilised in a future Smart Building environment, for instance, applications that can guide the building occupants during fire emergency situations. However, the initial focus should be on resolving key limitations in the FSE with BIM combination before adding Smart Building to the equation.

3 A STRATEGY FOR EFFECTIVE DATA SHARING BETWEEN BIM AND FSE

The literature review has identified key challenges and limitations facing the use and contribution of FSE in the context of BIM. Although there is reasonable support in BIM for the input data required for FSE, there is no explicit provision for storing and sharing the fire and evacuation modelling generated key fire safety analysis output data. On the other hand, the fire and evacuation modelling tools have limited support for BIM. Furthermore, there is a limited effort to resolve these issues and develop a systematic integration of FSE within BIM.

There is a need for a strategy that not only proposes a way to resolve the current limitations of data sharing between BIM and FSE in a step by step way to proceed towards the goal of Level 3 BIM i.e. fully integrated data exchange but also pave the way for future BIM with FSE enabled Smart Building applications.

The emergence of BIM has provided an opportunity to also address the limitations and problems related to how FSE is currently utilised in the AEC industry to avoid the future BIM developments from inheriting these issues and not being able to fully realise the potential benefits. For example, support for key fire and evacuation generated simulation data becoming part of the future IFC specification that can offer an opportunity to add a fire safety analysis layer to the Architectural model. In other words, a fire safety analysis sub-model that can provide information such as ASET and RSET values and exit usage for various scenarios based on the fire and evacuation analysis data. Moreover, this will allow FSE to become an important component of future Smart Buildings that can offer substantial benefits in terms of building management and safety. For example, the combination of BIM, FSE and Smart Building technology can identify near optimal evacuation information (Grandison *et al.*, 2017) for building occupants in response to an evolving emergency incident (Galea, Xie, *et al.*, 2017). An application of this technology is the proposal for the development of a BIM-enabled Smart Signage Management System.

3.1 Proposed strategy for FSE with BIM integration

The proposed strategy has been summarised in Figure 3.1.

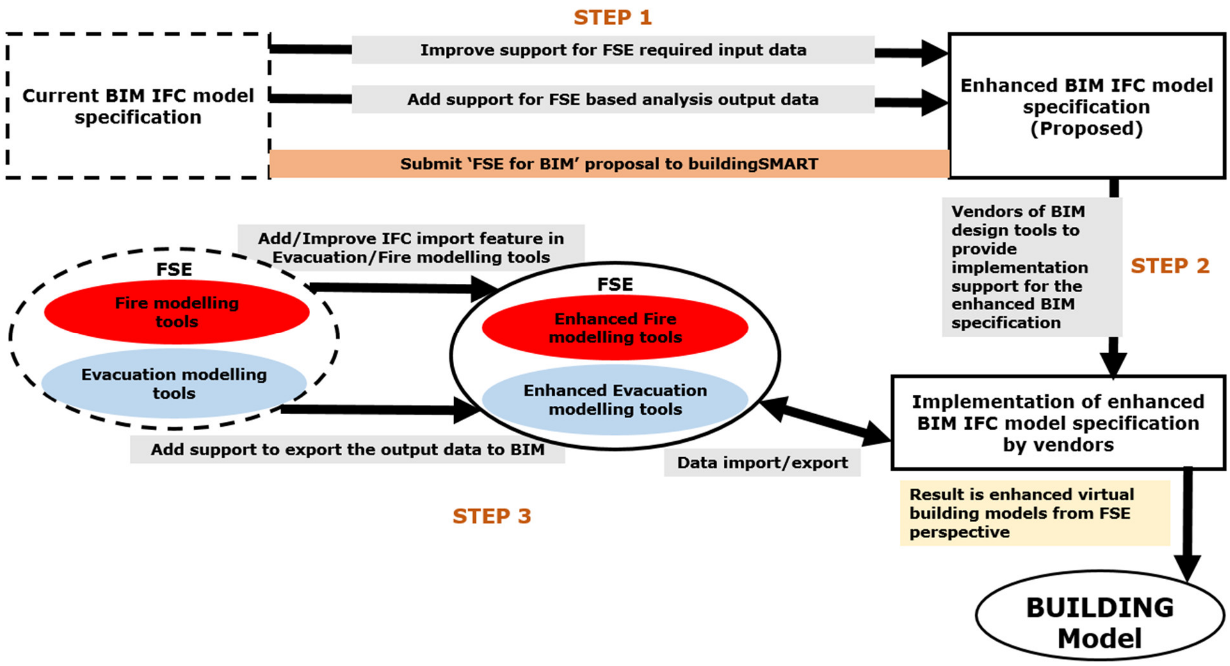

Figure 3.1: The proposed strategy for FSE with BIM data sharing

Before expanding on the steps shown in Figure 3.1, it is important to re-emphasize the MVD concept (buildingSMART, no date c) which was introduced in Chapter 2. Essentially, for particular information exchange, this concept provides a technical description as a subset of the IFC schema. The official MVDs are published by buildingSMART using the neutral mvdXML format. The current official buildingSMART developed MVDs (buildingSMART, no date d) are:

- For IFC4: IFC4 Reference View and IFC4 Design Transfer View which are the two successors of the IFC2x3 Coordination View v2.0.
- For IFC2x3: IFC2x3 Coordination View v2.0, Space Boundary Addon View, IFC2x3 Structural Analysis View and the IFC2x3 Basic FM Handover View.

In addition to the official MVDs, more MVDs are under development by organisations or teams which are not part of buildingSMART International.

To support in the technical specification development through MVDs, a number of information exchange projects (NIBS, no date b) were initiated. For instance, Electrical System information exchange (Sparkie), HVAC information exchange (HVACie) BIM Service interface exchange (BIMSie), Building Automation Modelling information exchange (BAMie), Building Programming information exchange (BPie), Life Cycle information exchange (LCie), BIM for PLM, Quantity Takeoff information exchange (QTie), Specifiers' Properties information exchange (SPie) and Wall information exchange (WALLie). This MVD concept is part of the strategy for FSE for BIM proposal as shown in Table 3.1.

Table 3.1: The proposed strategy for FSE with BIM data sharing

Step	
Step 1: Propose changes in IFC specification to support FSE	Propose an MVD for FSE specific data exchange to buildingSMART. A. Identify Input data required by fire and evacuation modelling tools for fire safety analysis. B. Identify key output data from fire and evacuation modelling tools.
Step 2: Implementation support for the proposed specification changes.	After successful adoption of the proposed changes to IFC specification, the BIM design tools vendors will be expected to provide implementation support for it.
Step 3: Provide support for BIM data exchange in fire and evacuation modelling tools.	This will include adding/enhancing capabilities of fire and evacuation modelling tools to make use of BIM-based data exchange. A. Acquire data from BIM for input in fire and evacuation modelling tools for FSE based analysis. B. Export/Write key output data generated by fire and evacuation modelling tools as part of FSE based analysis to BIM.

3.2 Step 1: Propose changes in IFC specification to support FSE

A building project offers different but often connected views of the same building. These views are like filters which are applied to cater for various disciplines. In case of FSE as well, a filtered view of the building is needed and the outcome of FSE based fire safety analysis can have an impact on a building's physical elements as well as how they are used and managed. The ideal approach is to have discipline specific views of a building where only the required data is provided. Similarly, the data returned by these disciplines should be filtered as well i.e. only able to modify/change what they are permitted to.

Improved support for the input data required for FSE based analysis and the availability of key FSE analysis results as part of the future version of the IFC Model will facilitate the stakeholders to make more informed, focused and relatively quick decisions. To initiate this, the author, as part of the FSEG, along with international project partners have been working on a proposal which has been initiated with buildingSMART. Even though this project is focussed on the FSE based analysis using fire and evacuation modelling tools, the scope of the proposal is wider as it includes movement of people in non-emergency situations as well. This can be important for FSE as it can help to define the population at the starting stages or a fire or emergency incident as well as providing an understanding of the building usage. A key part of identifying data requirements for MVD is the understanding of what input and output data is needed for FSE based analysis and what level of support there is in the current IFC Model. The idea is that once the MVD for FSE has been developed, it will provide a filtered view from the FSE perspective. Based on that understanding, a preliminary database can be developed that not only captures the key required data but also facilitates work on the proposal. In other words, this preliminary database can serve as an initial guide for developing MVD with input from the project partners to support FSE data. If the proposal is accepted by the buildingSMART then the development work on the proposal will lead to the introduction of an MVD (can be called 'Fire Safety Analysis MVD') that can potentially become part of the next version of IFC specification. How the currently unsupported FSE required data (mainly the analysis results) in IFC Model will be added in the next version depends on the development work as part of the MVD proposal with input from the buildingSMART. Nevertheless, the following two options can be considered:

Option 1: Support can be added in the Domain Layer of the IFC data schema architecture which can be referred to as 'Fire Safety Analysis'.

Option 2 (Preferred option): Support can be added in a new layer (can be called 'Simulation Layer') on top of the Domain Layer of the IFC data schema architecture. This new layer can cater for various types of simulations performed as part of the building development. The fire and evacuation modelling tools generated key simulation outputs are one of these types but others such as building energy analysis, lighting can also benefit from this approach.

The data input and output requirements for FSE based analysis and the current level of support for it in the IFC Model is covered in Chapter 4. Along with this, a description of the development work, in support of this step of the proposed strategy is also covered in Chapter 4.

3.3 Step 2: Implementation support for the proposed specification changes

This step depends on the successful completion of Step 1 i.e. introduction of MVD for FSE in the next version of the IFC Model specification. After the MVD for FSE has been released by the buildingSMART, the BIM design software vendors will be expected to provide support for the new MVD. This will not only include implementation support for the updated IFC specification but also an MVD for FSE export option in the BIM design tools. There is currently support in various BIM design tools for existing MVDs. For instance, in Revit, IFC export option supports several views such as IFC4 Reference View and IFC2x3 Coordination View v2.0 (Autodesk, 2018). Enhancing support for BIM is an ongoing process and therefore it is expected that the future versions of BIM design tools will offer more BIM related options.

Further to the description in Section 3.2 and above, it is important to emphasise that the current IFC Model Specification caters for a wide range of building elements which are required by various stakeholders involved in a typical building project. By utilising existing MVDs which are supported by various BIM design tools, required building data can be extracted and shared with stakeholders. It is possible to customise IFC import/export capabilities of these BIM design tools (e.g. Revit) to provide support for a draft implementation for FSE related data. However, what is needed is explicit support in IFC Specification for all the FSE required elements and properties. This explicit support in IFC Model Specification and through an FSE specific MVD, BIM design tools can provide the type of support which is not limited to one BIM package and for a specific project only. In other words, the outcome is a standard approach to data extraction and sharing from the FSE perspective.

3.4 Step 3: Provide support for BIM data exchange in fire/evacuation modelling tools

In this section, both parts i.e. A and B of Step 3 are covered.

Step 3 A - Acquire data from BIM for input in fire and evacuation modelling tools for FSE based analysis

As indicated in Chapter 2, most fire and evacuation modelling tools currently do not support the importing of data from an IFC file. Even those tools which have provided support for IFC, typically have their capabilities limited to basic building geometry extraction. Several examples of fire and evacuation tools currently offering an IFC import option were mentioned in Chapter 2. It is down to the vendors of fire and evacuation modelling tools to add or enhance their support for BIM. However, as far as the development work for this step of the strategy is concerned, evacuation modelling tool buildingEXODUS and fire modelling tool SMARTFIRE were selected and used as representative examples of evacuation and fire modelling tools in order to demonstrate support for IFC. The details are included in Chapter 4.

Step 3 B - Export/Write key output data generated by fire and evacuation modelling tools as part of FSE based analysis.to BIM

The work on this step depends on the inclusion of fire safety analysis output data in the next version of IFC specification and its support in various BIM design tools such as Revit (Autodesk, 2019), Vectorworks (Vectorworks, 2019), and ARCHICAD (GRAPHISOFT, 2019a). Moreover, the fire and evacuation modelling tools use various file formats to export their output data, some of which can be proprietary or may present technical challenges to acceptable long-term storage (e.g. due to size). However, for better support for BIM in the future, it is proposed that a suitable standard file format should also be utilised.

The details of the development work in support of this step are covered in Chapter 4.

3.5 Benefits of the proposed strategy

Figure 3.2 provides a summary comparison of the FSE with non-BIM, current BIM and enhanced BIM as a result of adopting the proposed strategy.

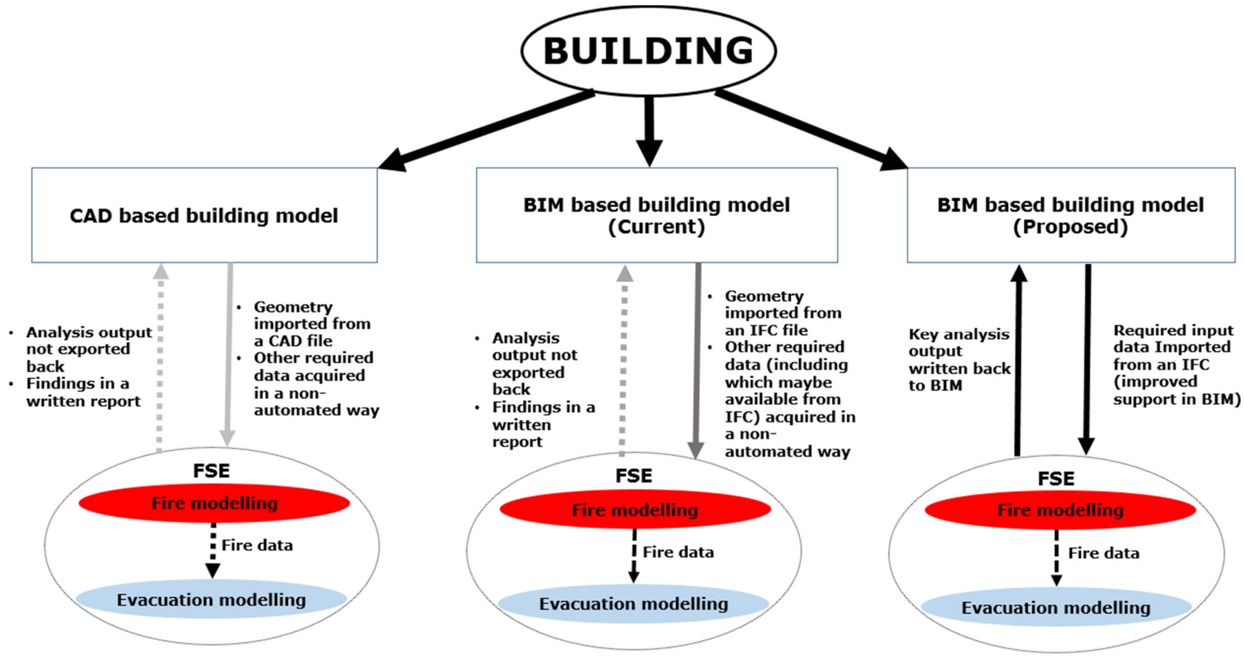

Figure 3.2: Comparison of FSE with non-BIM, current BIM and proposed BIM

The enhanced support for FSE in BIM and vice versa can have benefits at various phases during the building lifecycle, for instance, the following:

Benefits in the design phase

- Improved accuracy and quick access to information due to an enhanced level of support for FSE in BIM and vice versa.
- If the FSE based analysis simulation data becomes part of the future BIM IFC Model specification, then it can lead to the possibility of a building fire safety analysis sub-model which will allow focused data sharing with stakeholders facilitating informed decision making. Useful information such as exit usage for a scenario can be extracted for BIM and provided to the relevant parties. A quick visual representation of this type of information can be achieved by adding these details as a layer to the Architectural model which can then be called Fire Safety Analysis sub-model.
- This can lead to further future improvements such as achieving a certain level of automation in terms of checking fire safety aspects of design, rechecking in case of a change in building design (e.g. structural change or change in space use) – which can affect the fire safety of the structure.

- By capturing FSE based analysis simulation data as part of the BIM IFC Model, an audit trail from the FSE perspective can be kept. In other words, this can help in keeping a "*golden thread*" of information.
- Faster and more reliable process in terms of acquiring FSE required input data for the purpose of setting up scenarios and running simulations in fire/evacuation modelling tools.

Benefits in the operational phase

- During the operational phase FSE based analysis data stored in BIM can be used for the development of other building management support applications. The aspects of Smart Building technology with BIM and FSE combination can be utilised to facilitate the evacuation of occupants.

Benefits in forensic analysis

- Improved accuracy and quick access to the simulations data related to previously conducted FSE based analysis. This will help in analysing how the incident requiring forensic analysis compares with the analyses conducted during the building design.
- Availability of FSE based analysis simulation data in BIM will allow relatively quicker forensic analysis process.

Benefits in other phases (e.g. design change phase)

- Management of change (e.g. change of usage/occupancy and change due to refurbishment).
- Temporary changes, such as during maintenance or atypical events such as conferences with a larger number of building occupants than regular usage.

3.6 Summary

A three steps strategy for data sharing between BIM and FSE has been proposed in this chapter. This strategy has targeted three key areas to address the current limitations in BIM with FSE data sharing, namely IFC Model specification, BIM design tools for implementation support for the IFC specification, and fire and evacuation modelling tools for FSE based analysis respectively. Several additions and improvements are needed in these three areas to fully realise the benefits of BIM with FSE data exchange.

Step1 of the strategy focussed on the IFC specification in relation to its support for FSE. A proposal to develop an MVD for FSE data exchange is the key outcome of this Step 1. Step 2 is concerned with the implementation support by the BIM design tools vendors for the proposed changes in the IFC specification. Finally Step 3 is about adding/enhancing support for the BIM data exchange in fire and evacuation modelling tools.

The potential benefits of this strategy for various phases of building lifecycle were also mentioned. These benefits included improved accuracy and quick access to information, focused data sharing with stakeholders facilitating informed decision making, potential for the development of a certain level of automation in the future, and potential for the development of applications in the future involving a combination of BIM, FSE and Smart Building systems such as Smart Signage Management.

The strategy presented in this chapter addresses the identified gaps in knowledge for data exchange for FSE within the BIM context to use with fire and evacuation modelling tools. The development work in support of this strategy is covered in Chapter 4 that will also serve as a proof of concepts presented as part of this strategy.

4 DEVELOPMENT WORK TO SUPPORT THE STRATEGY

In this chapter, the development work in support of the strategy for BIM with FSE is covered. Each step of the strategy which was covered in Chapter 3 has been further discussed from the development work perspective in this chapter. This will also serve as proof of concept work for various aspects of the strategy. For each step of the strategy, the development work covering requirements analysis, design and implementation are discussed. Also, how the implementation work can be evaluated as part of a proof of concept work, is also presented. Furthermore, an application of BIM with FSE combination in a Smart Building environment is discussed. However, only a high-level conceptual design has been covered, as the implementation of this application is beyond the scope of this project due to time constraints and practical resources requirements.

4.1 Step 1: Propose changes in IFC specification to support FSE

The first part of the strategy is about the identification of the scope and data requirements for FSE within the BIM context to facilitate the development of the proposed MVD. It is therefore imperative to commence by tackling the FSE data requirements.

4.1.1 Analysis of FSE data requirements and support in BIM

In this section, FSE data requirements analysis, and analysis of FSE required data support in BIM are covered in separate sub sections.

4.1.1.1 FSE data requirements analysis

It is important to emphasize that the main contribution of FSE is at the initial building design phase, but it can also be utilised in case of a change in building design/usage, and fire incident forensic analysis. Fire Engineers usually conduct a fire safety analysis of buildings. This is not only for a new building at the design phase, but Fire Engineers may be required to perform a risk assessment of an existing building or when a building is modified in some way. Furthermore, Fire Engineers may also be involved in the investigation of certain fire events. Fire Engineers analyse fire safety aspects by applying scientific and engineering principles and utilising fire and evacuation modelling tools. These tools, depending on their capabilities, may require detailed data input covering various aspects of the building, including the geometry of the building design, material information, nature of the occupancy, number and nature of the occupants, evacuation routes, type of alarm, and proposed fire and smoke management systems. Moreover, the fire and evacuation analysis results, produced by these tools, have to be shared with architects and designers so that the design can either be approved or improved as appropriate.

The data input requirements to do FSE based analysis as well as the output have been indicated in research articles and standards such as (Morente, Quintana and Wald, no date; BSI, 2001; Spearpoint and Dimyadi, 2007; Gorbett, 2008; Anderson and Ezekoye, 2014). The British Standards framework BS 7974 for the application of FSE (BSI, 2001) is supported by a series of published documents that provide additional guidance on FSE, six sub-systems (1: Initiation and development of fire within the enclosure of origin, 2: Spread of smoke and toxic gases within and beyond the enclosure of origin, 3: Structural response and fire spread beyond the enclosure of origin, 4: Detection of fire and activation of fire protection systems, 5: Fire service intervention, and 6: Evacuation) and probabilistic risk assessment. The Subsystem 6 document PD 7974-6:2004, which covers the evaluation and management of human behaviour and condition in relation to evacuation during a fire emergency (BSI, 2004) was loosely used as a guide.

Presented in Figure 4.1 is a high-level overview of the role of FSE in building design and the following data categories it requires:

- Building geometry from the Architectural Model for both fire and evacuation modelling.
- Materials properties from the Structural Model for fire modelling.
- Smoke detection, warning and management information from the Building Services Model for fire modelling.
- Building usage.

Furthermore, the building design must adhere to regulatory requirements.

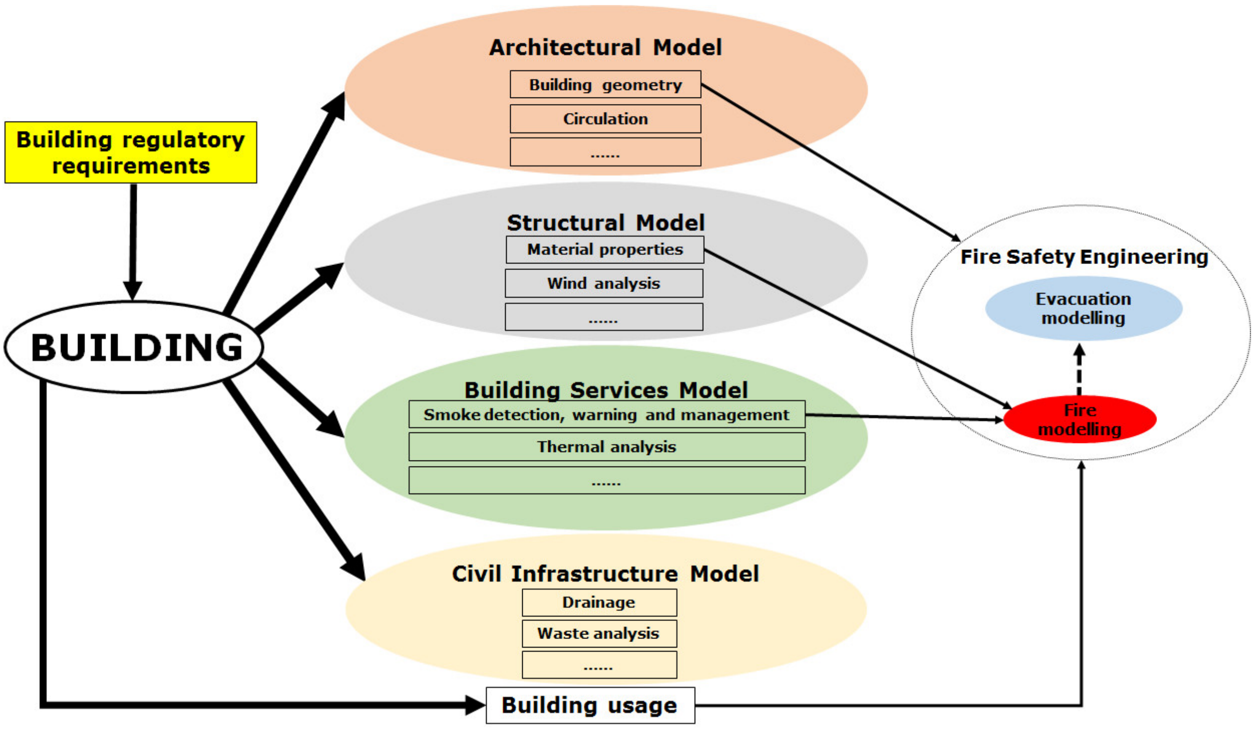

Figure 4.1: Overview of for the role of FSE during building design

After acquiring the required data, an expert user then undertakes fire safety analysis of a structure by utilising fire and evacuation modelling tools as part of FSE based assessment. It should be noted that acquiring the required data is not a straightforward automated process but instead a significant amount of manual work is needed. An overview of the use of fire and evacuation modelling in FSE for fire safety analysis in general terms is shown in Figure 4.2. It is important to understand that this is an iterative process where for each identified scenario, several simulations may need to be run. The data generated by these modelling tools is then interpreted by an expert user. This is a time consuming and challenging task. The results of the analyses are also likely to be interpreted and summarised in a Fire Strategy Report (sometimes also referred to as a Fire Safety Solution), so the actual simulation results are not available to anyone but the Fire Engineer who undertook the analyses.

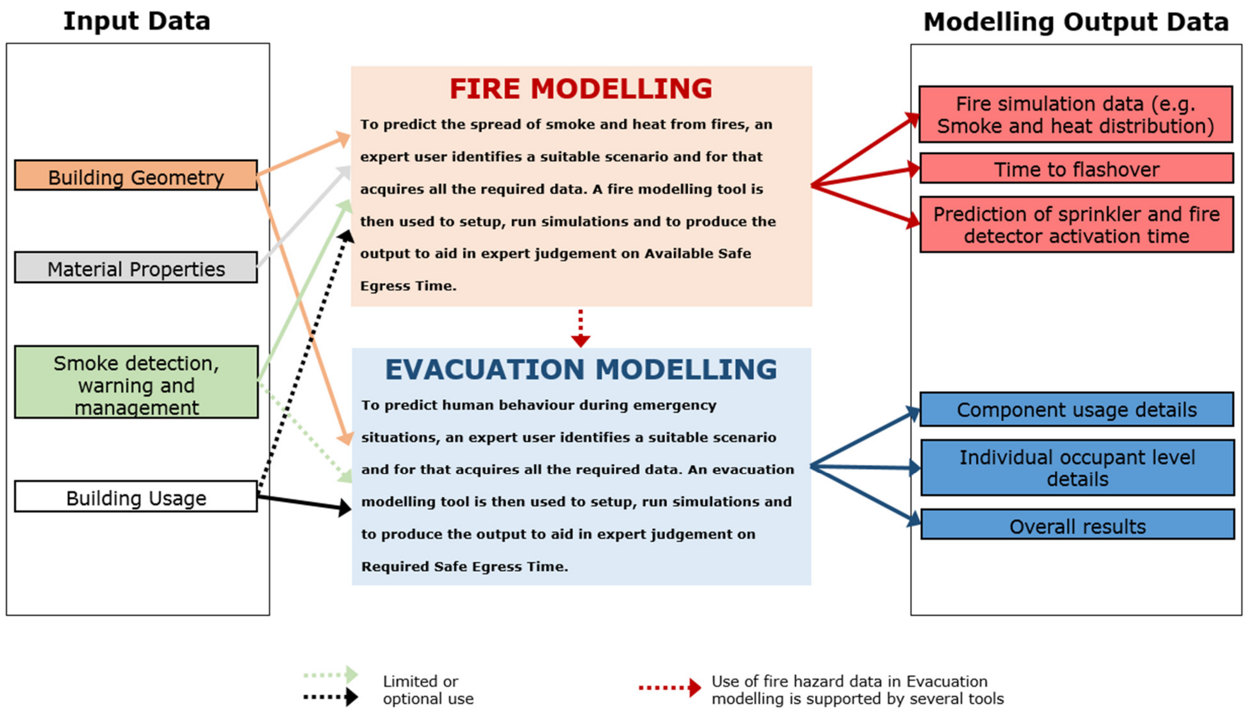

Figure 4.2: Overview of fire and evacuation modelling use in FSE for fire safety analysis

The characteristics of the fire, the building and its occupants are taken into consideration when evaluating safe evacuation (CFPA Europe, 2009). However, the data input considerations and output generated by the fire and evacuation modelling tools to establish performance metrics such as ASET and RSET depends on their current capabilities. The fire strategy may involve active (e.g. sprinklers) and passive (e.g. compartmentation) fire safety systems but also management systems (e.g. use of fire marshals, training and housekeeping) and so has implications to the future operation of the building.

A high level overview of the role of FSE in building design and then how it uses fire and evacuation modelling for fire safety analysis was presented in Figure 4.1 and Figure 4.2 respectively. Based on these two figures, the input data categories required for fire and evacuation modelling to aid in fire safety analysis are further expanded in Table 4.1 and Table 4.2. The input data categories required for fire and evacuation modelling to aid in fire safety analysis are shown in Table 4.1. Previous comparisons of evacuation modelling tools, as indicated in Chapter 2, have highlighted a significant difference in their capabilities. Similarly, there are significant differences in the capabilities of fire modelling tools and therefore not all of them support the level of data input mentioned in Table 4.1. Furthermore, currently acquiring input data mentioned in Table 4.1 and then utilising it in fire and evacuation modelling tools has a significant amount of manual work.

Table 4.1: Input data categories for fire and evacuation modelling tools

Data category	Subcategory	Fire modelling		Evacuation modelling	
		CFD	Zone	Coarse	Continuous
Building Geometry	Basic building components (e.g. Walls, Ceiling heights, Stairs and Lifts)	Yes	Yes[1]	Yes	Yes
	Vents (e.g. Doors and Windows)	Yes	Yes	Yes	Yes
	Fire safety related information (e.g. location of fire protection components and systems, load bearing indication for walls, etc.)	Yes[2]	Yes[2]	Yes[2]	Yes[2]
Material Properties	Thermo-physical properties of building structural components, fire rating indication, etc.	Yes	Yes	No	No
Smoke detection, warning and management	Fans, alarms and sprinklers activation situation	Yes	Yes	Yes[3]	Yes[3]
Building Usage	Fuels i.e. burnable items/fire sources in the building, including furnishings, coatings, wiring producing fire effluent. Hazard releases not related to fire, e.g. toxic gas release. Building components (e.g. coatings) may passively absorb hazards such as HCl or release others as they are thermally assaulted by the fire	Yes	Yes	No	No

Data category	Subcategory	Fire modelling		Evacuation modelling	
		CFD	Zone	Coarse	Continuous
	Obstacles/furniture in the building	Yes	No	Yes	Yes
	Number and distribution of occupants	No	No	Yes	Yes
	Occupants' characteristics and behaviour	No[4]	No	Yes	Yes
	Escape routes	No	No	Yes	Yes
	Signage	No	No	Yes[5]	Yes
	Building occupancy at day/night time hours	Yes[6]	Yes[6]	Yes	Yes
Other Considerations	Windows/Door failure changes ventilation	Yes	No	Yes	Yes
	Leakages	Yes	Yes	No	No
	Behaviour of the components (e.g. alarm activation conditions and sprinkler performance/activation)	Yes	Yes	No	No

[1] *The components like stairs and lifts are not included in Zone Models.*

[2] *The CAD/DXF file may contain the location of fire protection components and systems but this would be very limited, if present at all, and open to interpretation by the viewer.*

[3] *Currently, only alarm to indicate pre-movement times.*

[4] *Usually neglected but can have an impact (e.g. opening door to pressurised stairs).*

[5] *Signage is difficult to represent in the Coarse network approach.*

[6] *CFD/Zone modelling should not really be interested in the building occupancy though it may have some implications for where hazard data is needed for export.*

The following are additional but important considerations and observations including any deficiencies related to Table 4.1 above:

- For fire modelling, the level of data input requirements also depends on the type of fire model. CFD based models require considerably more detailed data than do Zone models. The data generated by fire modelling tools can vary due to the availability of different types of models and the level of sophistication that they offer. For evacuation modelling, the level of acceptable data input varies depending on the particular evacuation model. For example, the simpler models only require room connectivity and prescribed flow rates between compartments.
- The location of any fire protection components (e.g. sprinklers and alarms), as well as an understanding of the behaviour of the components, is required. For instance, the pattern of sprinkler activations due to smoke or heat detection, the flow rate, the droplet spread pattern and droplet size/trajectories for sprinklers. It is often also necessary to understand the geometry of the component (e.g. a smoke or temperature sensor) because this can have an impact on the activation of various fire safety systems as determined in the fire modelling simulation.
- There are two distinct aspects of fire hazards. In fire modelling, the sources of toxic species must also be specified, which are generally estimated from the type of fuel and the likely burning conditions; whilst the hazard spread is computed by the fire modelling software. Conversely, the evacuation modelling software requires as input the time and spatially varying concentration data of all the hazardous fire effluents and toxic species (as computed by the fire modelling software).
- Temporal changes such as when and/or under what conditions fans, alarms and sprinklers are activated are important inputs. The temporal data also applies to the population, i.e. are there differences in occupant behaviour, building occupancy and room usage based on the time of day, a particular day of the week or time of year?
- Consideration is also given to the issue of potential failures, which applies to doors and windows. For windows, the time and mode of failure will likely have a significant impact on the fire development.
- Sometimes, wall and floor surface coatings (e.g. paint and possible carpets) can be important due to their effect on the release or absorption of toxic species. This is a relatively uncommon consideration but for completeness, it is mentioned here and is becoming more important due to the increasing use of eco-friendly building materials that are better insulators, but also more flammable (e.g. recycled materials used in building insulation).

- Other aspects of the design which are needed include smoke management systems that may be dynamically activated such as fans, smoke curtains, smoke extraction systems and automatic or manually operated louvres/vents. Furthermore, air leakages (e.g. gaps under and around doors) and through walls and water supply characteristics (or smoke extract fan characteristics) may also be required.
- The difference between the Evacuation Modelling tools using the Coarse network and Continuous approaches to represent enclosure space is mainly related to precision. Therefore, in terms of the data input as well as the output, there is no real difference. However, signage is difficult to represent in the Coarse network approach.

Similarly, Table 4.2 provides information about the data output from fire and evacuation modelling tools as part of the fire safety analysis. As mentioned previously, the comparison of evacuation modelling tools (Kuligowski, Peacock and Hoskins, 2010) has highlighted a significant difference in their capabilities. Similarly, there are significant differences in the capabilities of fire modelling tools and therefore not all of them support the level of data output mentioned in Table 4.2.

Table 4.2: Output data categories for fire and evacuation modelling tools

Data category	Fire modelling		Evacuation modelling	
	CFD	Zone	Coarse	Continuous
Fire simulation data (e.g. Smoke and heat distribution)	Yes	Yes[1]	No	No
Time to flashover	Yes[2]	Yes[2]	No	No
Output of sprinkler and fire detector activation time	Yes	Yes[3]	No	No
Component usage details (e.g. Usage of exits)	No	No	Yes	Yes
Overall results (e.g. number of people safely out and number of fatalities/casualties)	No	No	Yes	Yes
Individual occupant level details (e.g. response time, distance travelled, death location/exited location, history of hazard exposure)	No	No	Yes	Yes

[1] *Limited to results in layers – implications for the analysis of population exposure.*

[2] *This may or may not be accurately determined by the model. Certain model and sub-model combinations will not be able to predict this.*

[3] *Often limited to simple trigger values as convective flows are not computed.*

4.1.1.2 Analysis of FSE required data support in BIM

The AEC industry is moving towards Level 2 BIM which is about collaboration. For instance, the UK Government's BIM mandate has significantly increased awareness and adoption of Level 2 on its sponsored projects in the UK (NBS, 2018) but from the FSE perspective, it is not fully fit for purpose. Furthermore, the goal is reaching BIM Level 3 which is about integration but that will require active participation and contribution from various disciplines and the BIM vendors. It is expected to take several more years to reach the desired level though parts of it are already being utilised such as the IFC file format for data exchange.

The data schema architecture of IFC provides a detailed representation of a building's structure and contents. It offers several options (e.g. objects and relationships) that are beneficial for integration with fire and evacuation modelling software. However, the simulation generated fire safety analysis data is not included within the current IFC version.

The support in BIM for the input data categories required for fire and evacuation modelling and the output generated by them is shown in Table 4.3 and Table 4.4. The review of IFC 2x3 and IFC4 from the FSE perspective by the author is included in Appendix A which should provide clarity in terms of what has been highlighted in Table 4.3 and Table 4.4.

Table 4.3: Input data categories for fire and evacuation modelling tools support in BIM

Data category	Subcategory	Fire modelling		Evacuation modelling		Supported in BIM
		CFD	Zone	Coarse	Continuous	
Building Geometry	Basic building components (e.g. Walls)	Yes	Yes	Yes	Yes	Yes
	Vents (e.g. Doors and windows)	Yes	Yes	Yes	Yes	Yes
	Fire safety related information (e.g. location of fire protection components and systems, load bearing indication for walls, etc.)	Yes	Yes	Yes	Yes	Yes
Material Properties	Thermo-physical properties of building structural components, fire rating indication, etc.	Yes	Yes	No	No	Yes

Data category	Subcategory	Fire modelling		Evacuation modelling		Supported in BIM
		CFD	Zone	Coarse	Continuous	
Smoke detection, warning and management	Fans, alarms and sprinklers activation situation	Yes	Yes	Yes	Yes	Yes
Building Usage	Fuels i.e. burnable items/fire sources in the building, including furnishings, coatings, wiring producing fire effluent. Hazard releases not related to fire, e.g. toxic gas release. Building components (e.g. coatings) may passively absorb hazards such as HCl	Yes	Yes	No	No	Some support
	Obstacles/furniture in the building	Yes	No	Yes	Yes	Yes
	Number and distribution of occupants	No	No	Yes	Yes	Yes
	Occupants' characteristics and behaviour	No	No	Yes	Yes	No
	Escape routes	No	No	Yes	Yes	Some support
	Signage	No	No	Yes	Yes	Yes

Data category	**Subcategory**	**Fire modelling**		**Evacuation modelling**		**Supported in BIM**
		CFD	**Zone**	**Coarse**	**Continuous**	
	Building occupancy at day/night time hours	Yes	Yes	Yes	Yes	Some support
Other Considerations	Windows/Door failure changes ventilation	Yes	No	Yes	Yes	Some support
	Leakages	Yes	Yes	No	No	No
	Behaviour of the components (e.g. alarm activation conditions)	Yes	Yes	No	No	Some support

- There is support in BIM in terms of building component information such as its location, material and further details that can be provided by the manufacturer.
- The property sets for objects in IFC (buildingSMART, 2016b) can be utilised to capture some building usage related information. For instance, for space within a building, property sets such as *Pset_SpaceFireSafetyRequirements* (Single value properties: *FireRiskFactor, FireExit, SprinklerProtection, SprinklerProtectionAutomatic* and *AirPressurization*) and *Pset_SpaceOccupancyRequirements* (Single value properties: *OccupancyType, OccupancyNumber, OccupancyNumberPeak, OccupancyTimePerDay, AreaPerOccupant, MinimumHeadroom* and *IsOutlookDesirable*) can be used.
- An information sign (e.g. exit sign) is represented as a furniture object in the current IFC version 4. Due to the importance of exit signage in fire safety and support in some evacuation modelling tools, maybe more details are needed [e.g. type (plain, reflective, illuminated, adaptive), purpose (exit route, no exit, other), associated speakers].
- Fire dampers are currently only vaguely represented within the current IFC version. It is one of the types of damper defined by the enumeration *IfcDamperTypeEnum*.
- Fire stopping representation is limited.

Table 4.4: Output data categories for fire and evacuation modelling tools support in BIM

Data category	Fire modelling		Evacuation modelling		Support in BIM
	CFD	Zone	Coarse	Continuous	
Fire simulation data (e.g. Smoke and heat distribution)	Yes	Yes	No	No	No[1]
Time to flashover	Yes	Yes	No	No	
Output of sprinkler and fire detector activation time	Yes	Yes	No	No	
Component usage details (e.g. Usage of exits)	No	No	Yes	Yes	
Overall results (e.g. number of people safely out and fatalities/casualties)	No	No	Yes	Yes	
Individual occupant level details (e.g. response time, distance travelled)	No	No	Yes	Yes	

[1] Some BIM packages such as Revit do provide options to add custom data sets to any element. However, there is no explicit support in BIM IFC for capturing the fire and evacuation modelling generated output data.

Along with international project partners, the author as part of FSEG has been working on a project proposal called 'MVD for Fire Safety Engineering and Occupants Movement Analysis'. Currently, the work is in progress on this collaboration project proposal to BIM standards organisation buildingSMART. As it can be noticed from the title of the proposal, non-emergency movement of occupants is also included even though it is not part of this research study. In other words, the proposal has a wider scope. The data requirements for FSE and its support in IFC covered here as part of the requirements analysis for Step 1 of the strategy will assist in the work suggested in the proposal.

4.1.2 Design work associated with the requirements analysis

The data categories required by FSE and their level of support in IFC was covered in Section 4.1.1. Based on that a preliminary design of the proposed fire safety analysis database schema is shown in Figure 4.3. It should be noted that for Figure 4.3, no specific database design notation was used, and a simplified diagram has been presented to aid in clarifying the concept. Another point that should be noted is that there are different types of Database Management Systems (DBMS) i.e. software for creating and managing databases with each having strengths and weaknesses (Ian, 2016a; Tweedie, 2018). The most widely used type of DBMS is the RDBMS which uses schemas to define relationships between the entities, which contain attributes. Even though there is growing competition from other types of DBMSs such as Not only Structured Query Language (NoSQL) which do not have a schema, RDMS still remains widely used. This work is for proof of concept and not yet for a production environment where performance and other factors such as storage can play an important part. Therefore, RDMS is a suitable option to use for this work.

The choice of data is not necessarily specific to a particular tool even though evacuation modelling tool buildingEXODUS and fire modelling tool SMARTFIRE were used as the primary options for guidance (see Table B3 and Table B4 in Appendix B). However, it is worth pointing out that three other evacuation modelling tools, namely MassMotion (Oasys, no date), Pathfinder (Thunderhead Engineering, 2018b) and STEPS (Mott MacDonald, no date b) were reviewed for this purpose as well, as they like buildingEXODUS, represents the small number of tools that support BIM IFC file import (see Table B1 in Appendix B). Similarly, for fire modelling, PyroSim (Thunderhead Engineering, 2019) was reviewed along with SMARTFIRE (see Table B2 in Appendix B). This is a preliminary design that mainly focuses on the FSE output data and covers a subset of the level of data presented in Table B3 and Table B4 in Appendix B. However, it can be expanded to capture more information (e.g. usage of other components such as stairs). Also, it can be refined and assist in producing the proposed MVD with feedback from the practitioners who are project partners for the project proposal to buildingSMART.

It is worth pointing out that unlike the basic review presented in Table B1 and Table B2 in Appendix B for evacuation modelling tools (MassMotion, Pathfinder, and STEPS) and fire modelling tool (PyroSim), a detailed list of data properties for them (similar to the one for buildingEXODUS in Table B3 and SMARTFIRE in Table B4 in Appendix B) can also be produced as part of the project proposal to buildingSMART (See the end of Section 4.1.1.2).

In Figure 4.3, there is provision for fire hazards since these can have a major impact on evacuation dynamics. A fire hazard can be associated with a zone. It is worth mentioning that in the IFC Model there is a 'zone' concept, which is a group of spaces, partial spaces or other zones. A zone (*IfcZone*) can be made up of multiple spaces (*IfcSpace*) objects and can be of various types (*FireCompartment*, *ElevatorShaft*, *RisingDuct*, *RunningDuct*). Consideration can be given to import zone related data (if available and the type and usage are clearly defined) from an IFC file in fire/evacuation modelling tools. This will reduce the time and effort required for adding and setting up data for analysis in fire/evacuation modelling tools. Using the database schema, it is possible to capture and share some key ASET, RSET, and coupled ASET/RSET analysis data. For instance, details of scenarios, simulations generated data such as exit usage, overall and simulated occupant level details, and fire hazard situation. It is important to point out that the scope of the database schema is dictated by the level of detail required. This means that some details may be considered essential, desirable or even unnecessary depending on the requirements. In cases where a large number of simulations are executed to find averages for evacuation, storing details of individual occupant level details will create a large amount of data that may deem unnecessary. On the other hand, in cases where the number of executed simulations for evacuation analysis is small, the individual occupant level generated data, particularly when the population number is not high, will not create a large amount of data. However, capturing individual occupant level details add clarity and provides an audit trail which is useful for future reference. Also, storing and processing large amounts of data is becoming more and more manageable. Based on this, simulated occupant level details are captured as shown in Figure 4.3.

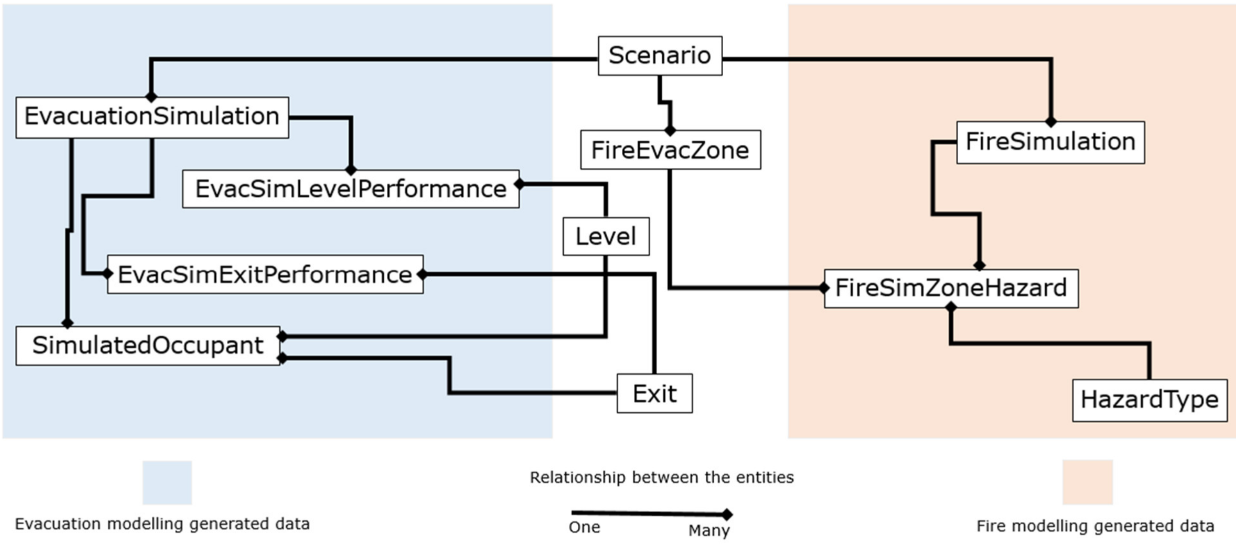

Figure 4.3: Preliminary design of database schema for FSE enabled fire safety analysis data

The entities shown in Figure 4.3 are listed in Table 4.5 with only some selected attributes and a brief description.

Table 4.5: Preliminary database schema with selected attributes and description

Entities	Attributes	Brief description
Scenario	ScenarioName, ScenarioDescription, AssumptionsMade	Basic details of scenario(s) identified for analysis.
FireEvacZone	FireEvacZoneName	List of zones for the identified scenario.
Level	LevelName	List of levels/floors.
Exit	ExitName	List of Exits.
EvacuationSimulation	EvacSimStartTime, EvacSimEndTime, TotalNumOfSimPeople, NumOfPeopleOut, NumOfFatalities	Some key overall information of the evacuation simulations which were executed for the identified scenario(s) is captured by this entity.
SimulatedOccupant	Gender, Weight, DistanceTravelled, ResponseTime	Individual simulated occupant details are captured by this entity.
EvacSimLevelPerformance	NumberStarted, LastExitTime	The overall usage of level during executed simulations is captured by this entity.
EvacSimExitPerformance	TotalNumberUsedIt, FirstOutTime, LastOutTime	The overall usage of exits during executed simulations is captured by this entity.
FireSimulation	FireSimStartTime, FireSimEndTime,	Some overall information of the fire simulation which was executed for the identified scenario(s) is captured by this entity.
FireSimZoneHazard	UpperValue, LowerValue, TimeInterval	The details of hazards at a specific time for specified fire zone during a simulation.
HazardType	HazardName, HazardDescription	The type of hazard (e.g. CO).

4.1.3 Implementation work in support of Step 1

To implement the database schema for the FSE based analysis data presented in Figure 4.3, a suitable DBMS is required. For the purpose of prototyping, as mentioned previously, RDBMS is a suitable type of DBMS. In terms of selecting a suitable RDBMS product for prototyping, there are various options but those that offer high performance are mainly server based and are unnecessary for this prototyping work. RDBMS such as Microsoft Access (Microsoft, no date) which allows relatively quick prototyping is a suitable option and therefore it was selected. However, for a production environment, a powerful RDBMS such as MySQL (MySQL, no date) could be used. As Structured Query Language (SQL) is the language used by all RDBMSs, transferring of database structure from one product to another will not be a complicated process in this case. The implemented FSE based analysis database relationship diagram is shown in Figure 4.4:

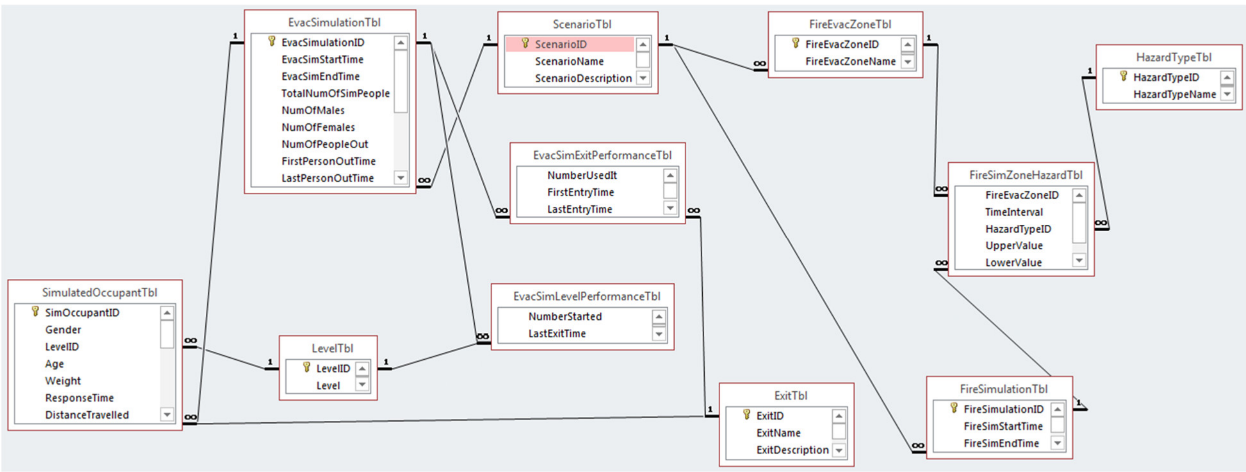

Figure 4.4: Screenshot of the database relationship diagram in MS Access

Note: The fire and evacuation simulation generated output files can also be attached to the database for future reference. For the full list of tables and fields, see Table B5 in Appendix B.

4.2 Step 2: Implementation support for the proposed specification changes

As mentioned in Chapter 3, Step 2 is dependent on the successful completion of Step 1 i.e. addition of MVD for FSE in the next version of the IFC Model specification. After the MVD for FSE has been released by the buildingSMART, the BIM design software vendors will be expected to provide support for the new MVD. This will not only include implementation support for the updated IFC specification but also an MVD for FSE export option in the BIM design tools.

There is currently support in various BIM design tools for existing MVDs. For instance, the following leading tools have support for several MVDs:

- Revit IFC export option support several views such as IFC4 Reference View and IFC2x3 Coordination View v2.0 (Autodesk, 2018).
- Vectorworks 2018 supports export to IFC versions 2x2, 2x3 and 4. There is support for a number of MVDs such as IFC4 Reference View, IFC 2x3 Coordination View v2.0, and Extended Vectorworks Model View which is not an official buildingSMART MVD (Vectorworks, 2018).
- ARCHICAD IFC export and import supports the following MVDs: IFC2x3 Coordination View 2.0, IFC4 Reference View, IFC4 Design Transfer View, IFC2x3 Coordination View (Surface Geometry) which is a subset of Coordination View, IFC2x3 Basic FM Handover View, and other MVDs (e.g. Concept Design BIM 2010) developed by organisations outside of buildingSMART (GRAPHISOFT, 2019b).

Improving support for BIM in leading tools is an ongoing process. The vendors of BIM design tools are also looking at ways to add improved support for BIM. One example of this is the project Quantum by Autodesk for cloud based BIM (Day, 2017).

4.3 Step 3: Provide support for BIM data exchange in fire/evacuation modelling tools

In this section, related to Step3 of the strategy, the following are covered in separate subsections: analysis, design work associated with the requirements analysis, and the implementation.

4.3.1 Analysis of Step 3 of the strategy

In this section, both parts i.e. A and B of Step 3 of the strategy are covered from the analysis perspective. An indication with a brief description of the evacuation and fire modelling tools selected for the development work in support of the FSE with BIM is also included.

Part A of Step 3 – BIM data import in fire and evacuation modelling tools

Part A of Step 3 is about adding/enhancing capabilities of fire and evacuation modelling tools to import BIM data. It was highlighted in Chapter 2 and Chapter 3 that only a few fire and evacuation modelling tools currently support importing of data from an IFC file. Even those tools which have provided support for IFC, typically have their capabilities limited to basic building geometry extraction. It is important to re-emphasize that providing support for IFC import is down to the vendors of fire and evacuation modelling tools.

For the development work in support of the FSE with BIM, evacuation modelling tool buildingEXODUS and fire modelling tool SMARTFIRE were selected as broadly representative systems.

buildingEXODUS

The buildingEXODUS, developed by the FSEG, is an evacuation modelling software. It is part of the EXODUS suite of software tools which are used to simulate population behaviour and movement in large complex spaces. The model tracks the path and trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The buildingEXODUS can be used for the following: to demonstrate compliance with building codes, evaluate the evacuation capabilities of all types of structures, and investigate population movement efficiencies within structures. To determine the behaviour and movement of individuals, a set of heuristics or rules are categorised into the following five interacting sub-models: Occupant, Movement, Behaviour, Toxicity and Hazard (Galea, Lawrence, *et al.*, 2017).

SMARTFIRE

The SMARTFIRE software is a suite of inter-coupled tools that allow a user to create, simulate and interrogate fire simulation problems. The components and their user interfaces allow users to specify a fire simulation geometry and scenario, to create a suitable CFD mesh and then to simulate the effects of the fire scenario over time or for steady state conditions.

The SMARTFIRE software suite currently has the following four main components: (1) a scenario designer for importing CAD drawings in a 2D geometry design system, (2) a front end case specification environment to configure the physical behaviours and sub-models required in the scenario, (3) an automated interactive meshing system to help create a suitable computational mesh, and (4) the CFD numerical engine to process the scenario as the simulation advances through time. The four SMARTFIRE components are usually used in the order presented above in a typical CFD simulation cycle. This consists of the creation and specification of the geometrical information describing the problem, creation (and possibly fine tuning) of a suitable mesh by the meshing tool followed by simulation of the problem in the CFD engine. The case specification environment handles the problem specification, the automated meshing system creates a mesh for the current geometry and the simulation is performed in the CFD engine. The scenario designer can also be used to import building designs from DXF CAD drawings (Ewer *et al.*, 2013).

Part B of Step 3 – Export/Write FSE based analysis data to BIM

Part B of Step 3 is about exporting/writing key output data generated by fire and evacuation modelling tools as part of FSE based analysis to BIM. In terms of an export option to output the FSE based analysis data to BIM, there is currently no explicit support in BIM design tools and the fire and evacuation modelling tools also offer no such facility. However, the implemented FSE based analysis preliminary database can be utilised to capture this data.

4.3.2 Design work associated with the requirements analysis

A description of the IFC import capability in buildingEXODUS and SMARTFIRE from the design perspective is covered here. First and foremost, it is important to make it clear that the work on developing this feature was not undertaken by the author. However, as it is related to the proposed strategy, it has been mentioned here for the purpose of clarity and completeness. Moreover, as this work is related to the proposed strategy, currently the capabilities are further developed as a result of the recommendations put forward by this work.

4.3.3 Implementation work in support of Step 3

An important point to be noted here is that no agreed upon standard approach is currently used by the fire and evacuation modelling tools for output data structure, level of detail, and the output file formats. One possible reason for this is the lack of an organisation guiding the developments and controlling these standards.

Part A of Step 3 – BIM data import in fire and evacuation modelling tools

The buildingEXODUS software is one of the few evacuation modelling tools which have implemented IFC file import functionality. To achieve IFC import functionality in buildingEXODUS, a third party library IfcOpenShell (IfcOpenShell, no date) was utilised. By using the IfcOpenShell, the ability to read building geometry data was implemented. It has been tested for a small subset of the elements in the IFC file which the user can then selectively filter further. However, it could be extended to include more elements, retain the 3D geometry or extract semantic information as required. An example is extracting the *IfcSpace* elements and constructing a connectivity graph from the *IfcRelSpaceBoundary* relationships. The capability of this tool is being further improved through the addition of automatic extraction of components such as staircases and lifts to speed up model generation. Furthermore, the automatic extraction of compartment/room connectivity will allow for an improved agent (a person is called an agent in simulation) spatial navigation, route decision making and cognitive models. The capability of the IFC import utility will be extended to extract smoke management components location information and furniture elements.

The development work on importing an IFC file in SMARTFIRE is, at the time of writing, a work in progress. For now, a command line application has been developed using IfcOpenShell that reads an IFC file and exports a DXF floor plan for each *IfcBuildingStorey* found. The floor plan is generated from a projection of the IFC Building and Furniture elements onto the horizontal plane. A separate DXF layer is then created for each IFC element type. Currently, the 3D information inherent in IFC is not retained. The DXF layers for each storey are then simply imported into SMARTFIRE Scenario Designer to use as a template for constructing the geometry in the usual way. As this functionality is currently a prototype and work in progress, it is for internal FSEG use only but it will be made available as part of the next version of SMARTFIRE in the near future.

Part B of Step 3 – Export/Write FSE based analysis data to BIM

Fire and evacuation modelling tools use different approaches in terms of how their data output is structured, the level of detail, and even the output file formats. It will be highly beneficial if a structured open data format approach is adopted as that will facilitate data sharing and can provide data integration in the future. In SMARTFIRE, the fire hazard data is output in the DAT file format for use in buildingEXODUS. On the other hand, buildingEXODUS output evacuation simulation data in the SIM file format. The fire hazard data in the DAT format output by SMARTFIRE can be imported in buildingEXODUS for analysis where the impact of fire on the occupants is required i.e. in coupled ASET/RSET analysis. However, as there is no standard data structure and format approach across various tools available in the market, both buildingEXODUS and SMARTFIRE also follow a native approach. As mentioned previously, the FSE based analysis preliminary database does allow this data to be captured which can then be queried using standard database language SQL.

To evaluate the development work in support of the proposed strategy, a prototype system was developed which is discussed in the following section.

4.4 Prototype system to evaluate the development work

In this section, related to the prototype system, the following are covered in separate subsections: requirements and design, and the implementation.

4.4.1 Requirements and design of the prototype system

To demonstrate the data sharing between BIM and FSE utilising the development work done as part of the strategy, a prototype system was developed. This proof of concept system uses the implemented database of FSE based analysis data, fire and evacuation modelling tools SMARTFIRE and buildingEXODUS respectively. As mentioned previously, the National Institute of Building Sciences (NIBS), which is part of the buildingSMART alliance, has been working on various information exchange projects to identify data requirements and provide specification/recommendations. One of these information exchange projects is called BIM Service interface exchange (BIMSie) which is the standard Application Programming Interface (API) for cloud based BIM web services (NIBS, no date a). However, it should be noted that the cloud based BIM is currently at an early stage of interoperability research (Afsari, Eastman and Shelden, 2017). Despite that, a number of server based products utilising aspects of BIMSie are available according to buildingSMART (2019a). Some of these products are freely available such as the BIMserver (BiMserver, no date) which is open source and offers a platform based on plug-ins and relies on IFC data stored in a database. This makes BIMserver a suitable platform to facilitate the proof of concept work to develop fire and evacuation modelling based web services for effective data sharing between BIM, and any suitable/compatible fire and evacuation modelling tools such as SMARTFIRE and buildingEXODUS utilising the FSE based analysis database.

Figure 4.5 presents a conceptual design of the prototype system to demonstrate data sharing between BIM and FSE by utilising BIMserver, buildingEXODUS and SMARTFIRE and the FSE based analysis database.

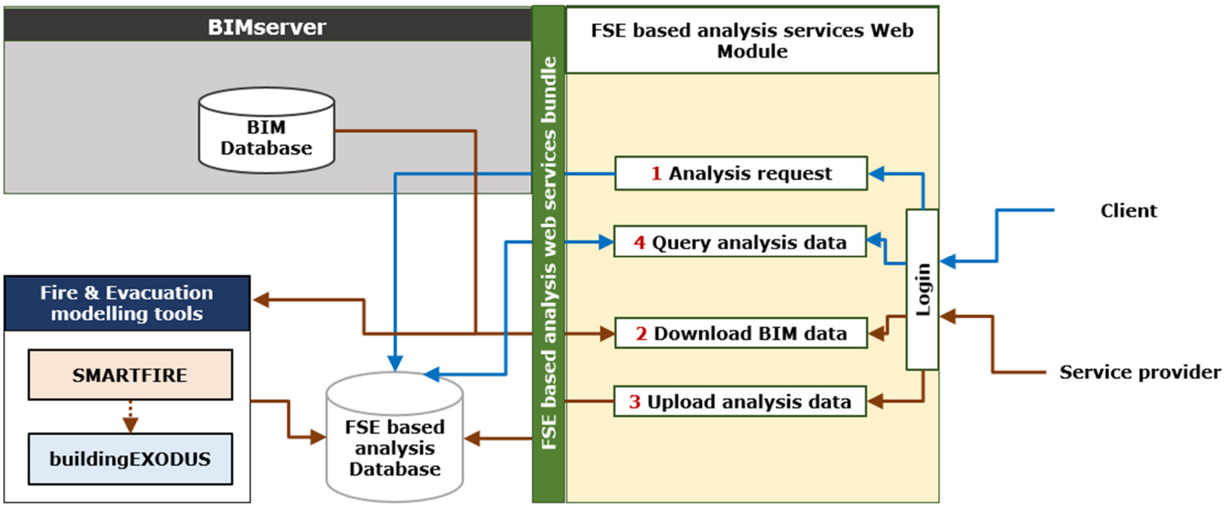

Figure 4.5: Conceptual design of the prototype system for data sharing between BIM and FSE

A description of the development work in support of the strategy has been covered already but to evaluate the data sharing between BIM and FSE, web services and web frontend were created as shown in Figure 4.5 above. This system allows the client to submit a request for FSE based analysis which is then recorded in the FSE based analysis database. Depending on the type of analysis (ASET, RSET, or coupled ASET/RSET), SMARTFIRE and/or buildingEXODUS are used to conduct the requested analysis. The results of the analysis are then added to the FSE based analysis database and are then shared with the client. To process this, a services bundle was created that works with the BIMserver using BIMserver Java Client API. The frontend facilitates this communication by allowing admin users to call the services in this bundle to process the requests. These services communicate with the FSE based analysis database which contains the data generated by the fire and evacuation modelling tools SMARTFIRE and buildingEXODUS respectively. The frontend works on this concept where a role oriented FSE specific view of the building project can be provided. This system can be used for testing data sharing between BIM and FSE at the building design phase, in a situation where there is a change is design, and even for a fire incident forensic analysis. Furthermore, some aspects of this system can be utilised for testing data sharing between BIM and FSE in a Smart Building environment during the building's operational phase.

The FSE based analysis web services bundle can provide several services to clients as shown in Figure 4.5. These services once registered with the BIMserver and attached to the selected building project, will be able to use BIM-enabled data. In case of a design change (e.g. change in building usage or in geometry), the client can request an expert assessment of whether ASET/RSET reanalysis is needed. If reanalysis is needed, then it is undertaken for the suggested design change. The client will then be able to run queries and able to see the comparative outcome of the proposed change.

4.4.2 Implementation of the prototype system

This type of system can be hosted in more than one way with each having strengths and weaknesses but depending on the requirements, one can be a better option than the other. The following are the options:

Option 1: Host the services bundle and the frontend on the same instance of BIMserver which can interact with the FSE analysis database. In other words, all the components including the database are hosted locally. This is a good option for prototyping.

Option 2: For this, a BIMserver instance to host the BIM based data and another server (e.g. another instance of BIMserver) externally deployed to host the services bundle and the FSE based analysis database. This can be a suitable option for a production environment. However, the hosting of the FSE based analysis database requires some consideration. If it is hosted with the BIMserver then it means it will remain under the client's control. On the other hand, if the database is hosted by the service provider then the client will not have the same level of control.

For the proof of concept work, option 1 is suitable as options 2 is more relevant in a production environment. Option 1 in terms of setup is better for the purpose of testing. If in the future, there is a need to deploy this system in a production environment then option 2 will be the more suitable option. For now, using option 1, the prototype system can demonstrate data sharing between BIM and FSE. The frontend is HTML/JavaScript based which utilises BIMserver JavaScript Client API to communicate with BIM i.e. using BIMserver open source framework and its services/plugins. The following main steps are included in the front end:

1. Client submits FSE based analysis (ASET, RSET, or coupled ASET/RSET) request.

2. Service provider (e.g. FSEG) acquire the input data (i.e. download the IFC file from the BIMserver). Depending on the type of request, the downloaded IFC file will then be imported in SMARTFIRE and/or buildingEXODUS.
3. Service provider uploads analysis data to the analysis database. Currently, this is not an automated process but with further development work, a capability to select fire and evacuation generated simulation output files by buildingEXODUS and SMARTFIRE, from the frontend and then the key data in them is added to the database. Another consideration is to output the fire and evacuation generated output data in a commonly used standard file formats such as JavaScript Object Notation (JSON) (w3schools, no date a) or eXtensible Markup Language (XML) (w3schools, no date b) instead of the currently used native DAT and SIM formats in SMARTFIRE and buildingEXODUS. However, with future support for FSE based analysis data in IFC specification and its implementation by the BIM design tools vendors, this data can be exported to the BIM database. For this to work, the BIM design tools vendors have to offer a capability to import/load the FSE based analysis data from a suitable file format. One possibility is for fire and evacuation modelling tools to add the FSE based analysis data to the imported IFC file and then export it. This IFC file can then be imported in the BIM design tools. This can be a filtered approach where the data scope is set by MVD for FSE. Of course, this is only possible if supported by all the concerned parties i.e. buildingSMART for MVD for FSE specification, BIM design tools vendors for the implementation support for the MVD for FSE, and the fire and evacuation modelling tools vendors. Once the analysis data has been added to the database, an expert interpretation of the analysis results is provided by the service provider. Currently, the overall conclusion and the interpretation of results for each scenario is added in the database manually. However, an additional option can be added to the service provider interface as part of the future development to allow this information to be added through the frontend. Another important point to be noted here is that an additional service was created as a test to offer a facility to calculate ASET value based on the analysis data that has been entered in the database. The idea of this feature is to use a combination of database query and some additional code as part of the web service to calculate the ASET value for a particular scenario. This web service can be run after the analysis data has been entered in the database. However, currently, this whole

process of uploading analysis data, running service to calculate ASET/RSET values and then adding an expert interpretation of the results, is not automated.

4. The client initiates a query of the analysis data from a list of queries provided.

To implement the FSE based analysis web services bundle, Eclipse (Eclipse Foundation, no date) Integrated Development Environment (IDE) was used. Considering these web services are developed in Java Programming Language, use of Eclipse IDE was a suitable choice. The BIMserver comes with a Java Client API that allows communication with the BIM database which uses key-value store database (a type of NoSQL DBMS) (Ian, 2016b) Oracle Berkeley Database Java Edition (Oracle, no date) mainly due to its performance benefits over RDBMS. The BIMserver also has a JavaScript API for web-based communication with the BIM database.

Several services as part of the FSE based analysis web services bundle have been created. The code for these services was written in Java Programming Language and current bundle contain around 18 Java classes including helper classes for performing some common and repetitive tasks such as connecting to the database and sending notification emails. This services bundle has been created using BIM Bots (Bimbots, no date) service approach of BIMserver (BIMserver, 2017) which is their recommended way of using remote services. The concept behind BIM Bot is that it is an online service that can be triggered by an event and can perform some form of intelligent task related to BIM data (Bimbots, no date). As mentioned previously, for this prototype system, to ease in the development and testing, the BIMserver was deployed locally. Therefore, the services in the bundle, even though they can be deployed remotely, will instead be attached as internal services for BIMserver to communicate with the FSE based analysis database and process analysis and query requests. Another aspect of BIMserver which is important to mention here is their ‘Extended Data Schema’ concept (Laat, no date) which is a way of sharing data using specified data formats between different BIM software packages. This is a BIMserver specific approach and terminology. They have provided a list of some Extended Data Schemas but some of them have no formal specification. The idea is to attach to BIMserver, a file with a specified extension, containing data which is structured according to a specific schema. However, BIMserver has not provided any formal way of checking whether the data conforms to the specified schema, so it is up to the developers to ensure that this is consistent. Considering BIMserver uses BimBot and Extended Data Schema approach for attaching additional data to the BIM database, an Extended Data Schema was created for the FSE based analysis data for the testing purpose. The following two options were considered for this Extended Data Schema: 1) One file containing data for each request type, 2) separate file for each request type. Option 2 was selected because it provides more clarity by separating each request type. The name selected for this Extended Data Schema is 'FIRE_EVAC_SIM_DATA_JSON' and as the name suggests, has application/json as its content-type. The JSON format, which is lightweight, text only and easy to understand, is commonly used for browser and server data exchange. The JSON structure used for various type of requests for this prototype system is included in Appendix C.

A web frontend called 'FSE based analysis services Web module' for BIMserver has been developed as well. This HTML and JavaScript based web frontend use BIMserver JavaScript API to call these services and establish communication with the BIMserver. Some screenshots of the FSE based analysis services Web module are included here starting with Figure 4.6.

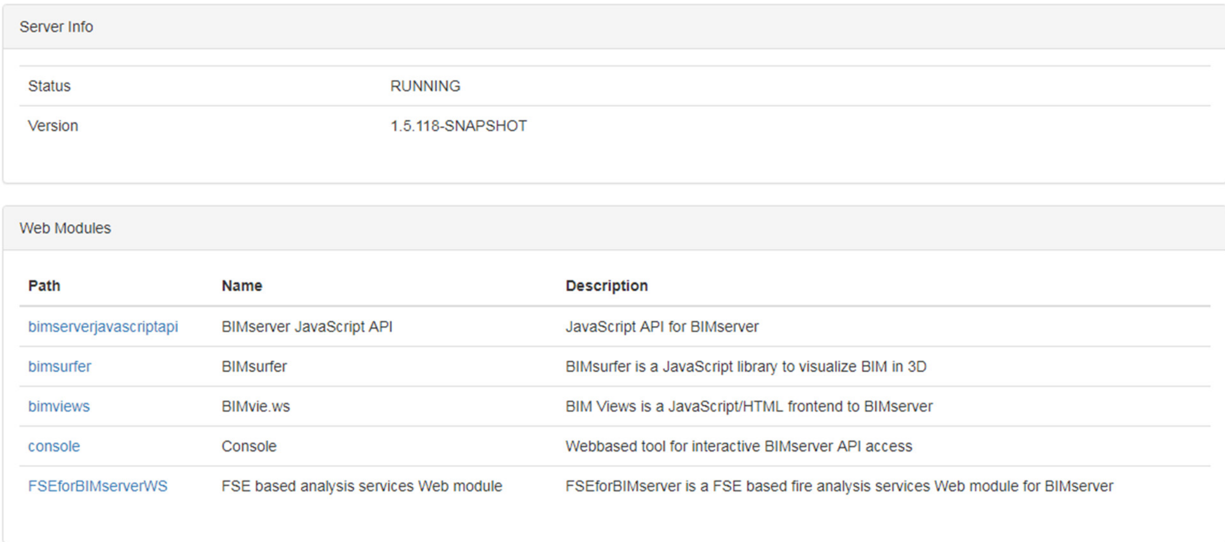

Figure 4.6: Locally running BIMserver default web page

The BIMserver is a Java application that can be launched locally from within Eclipse IDE which is convenient during the development phase or by simply double clicking the executable JAR (Java archive) file. After starting the BIMserver on a specified port, it can be accessed from a web browser. It comes with some plug-ins including Web Modules to provide functionality. On the default web page of the running BIMserver, available Web Modules are listed. The FSE based analysis services Web module which has been developed as part of this prototype system is listed as one of the Web Modules in Figure 4.6. One of the Web modules which comes with BIMserver is BIMvie.ws (Bimvie, no date) is compliant with the BIMSie API for BIM web services. It is a JavaScript/HTML frontend which works with BIMserver and offers several features to authorised users. For instance, create new projects, add revisions, check-in, visualise, download, install plug-ins, attach services, and admins user to add new users and assign access rights.

These Web Modules can be accessed from the default page or directly. Two options were considered in terms of how the available features of FSE based analysis services Web module can be made available to the authorised users. The first option was to have only one frontend with all the options which can be enabled/disabled based on whether the user is a client admin or service provider admin. The other option was to have a separate frontend for the client and for the service provider. The screenshot shown in Figure 4.7 is for the second option i.e. the one with separate frontends.

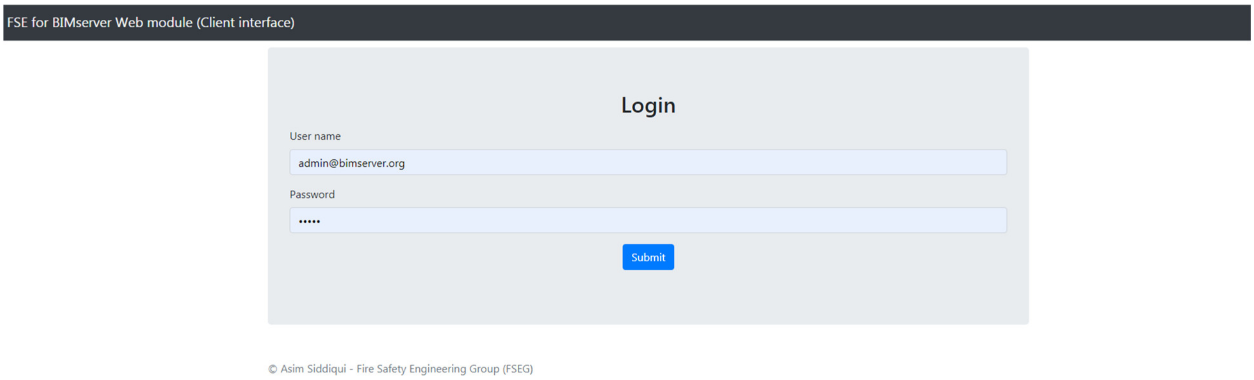

Figure 4.7: Login page for FSE for BIMserver Web module (client interface)

As mentioned previously, user accounts to access the BIMserver can be created by the admin user through BIMvie.ws. The login form shown in Figure 4.7 allows authorised users to connect to the BIMserver and access BIM data. A similar login page to the one shown in Figure 4.7 was created for the other frontend i.e. the one for the service provider. After the successful login, the page shown in Figure 4.8 is displayed.

Figure 4.8: Intro page for FSE for BIMserver Web module (client interface)

A similar page to the one shown in Figure 4.8 but with some essential changes is displayed in Figure 4.9.

Figure 4.9: Intro page for FSE for BIMserver Web module (service provider interface)

The client can select the project from the drop-down list (retrieved from the BIM database) for which FSE based analysis is needed, see Figure 4.10. A contract between the client and the service provider containing details of the required analysis is expected to be in place so what this option does is it allows a link to be established between the selected building project in BIMserver and the FSE based analysis database. One of the web services in the FSE based analysis web services bundle which is connected with this option processes the request. The web service connects to the FSE based analysis database to check whether a request has already been recorded in the database and if not then it is added. This request is also captured in a JSON file and attached to the BIMserver as extended data. If the request was previously captured in a JSON file then a new file is not created. Note: The Extended Data Schema approach of BIMserver has already been discussed in this chapter.

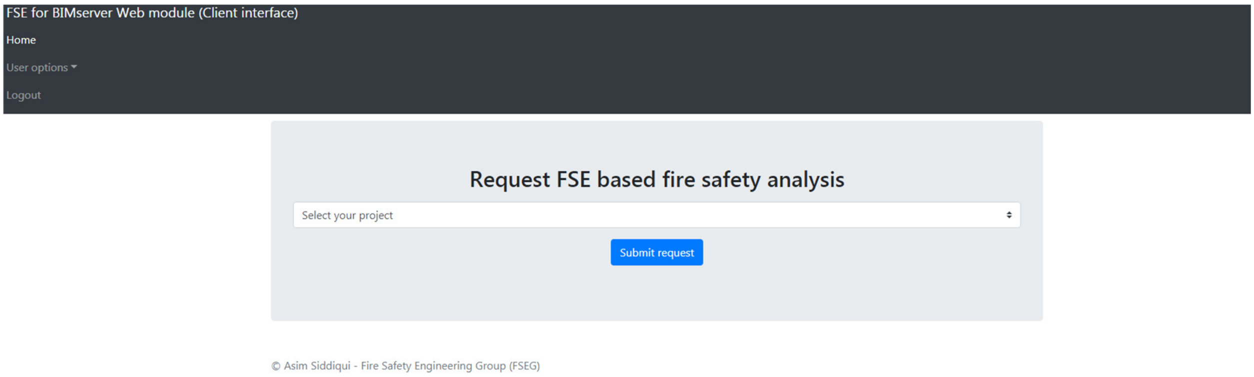

Figure 4.10: Analysis request page for FSE for BIMserver Web module (client interface)

After the FSE based analysis has been completed and analysis data has been added to the database, the client can interrogate the output data by selecting an available query from the drop down list as shown in Figure 4.11. The list of queries is retrieved from the FSE based analysis database by a web service in the services bundle. The results of the selected query which are retrieved from the FSE based analysis database are then displayed to the client. As with the analysis request, a list of queries and results are also captured in a JSON file and attached to the BIMserver as extended data.

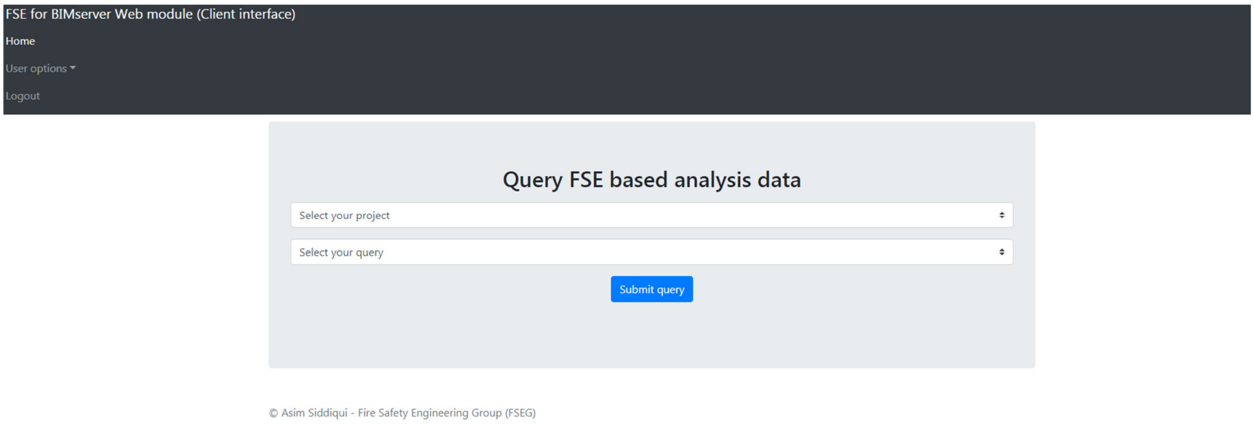

Figure 4.11: Query page for FSE for BIMserver Web module (client interface)

The service provider can acquire the input data for FSE based analysis from BIM by downloading the building data file (e.g. IFC file) from the service provider frontend, see Figure 4.12.

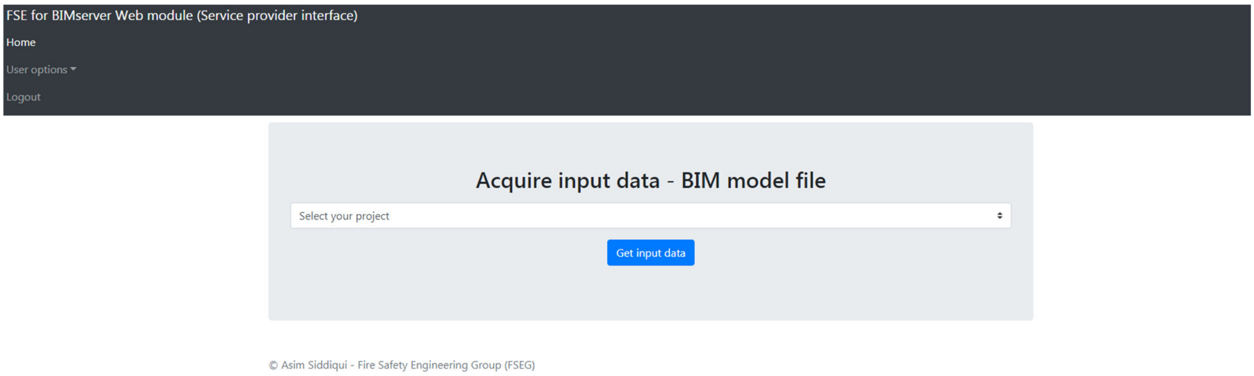

Figure 4.12: Acquire BIM data page for FSE for BIMserver Web module (service provider interface)

Depending on the type of analysis request, the downloaded IFC file containing the BIM data can then be imported in SMARTFIRE and/or buildingEXODUS for setup and analysis work. Currently, this is not an automated process.

The page for selecting and uploading fire and evacuation modelling generated output files for the service provider is shown in Figure 4.13. It should be emphasized that even though this page has been created, this feature has not been implemented. This is because of the significant amount of additional development effort needed to implement this. Also, as the outcome of MVD for FSE project proposal will have a direct impact on this type of development, it was decided that it is best to tackle this work later.

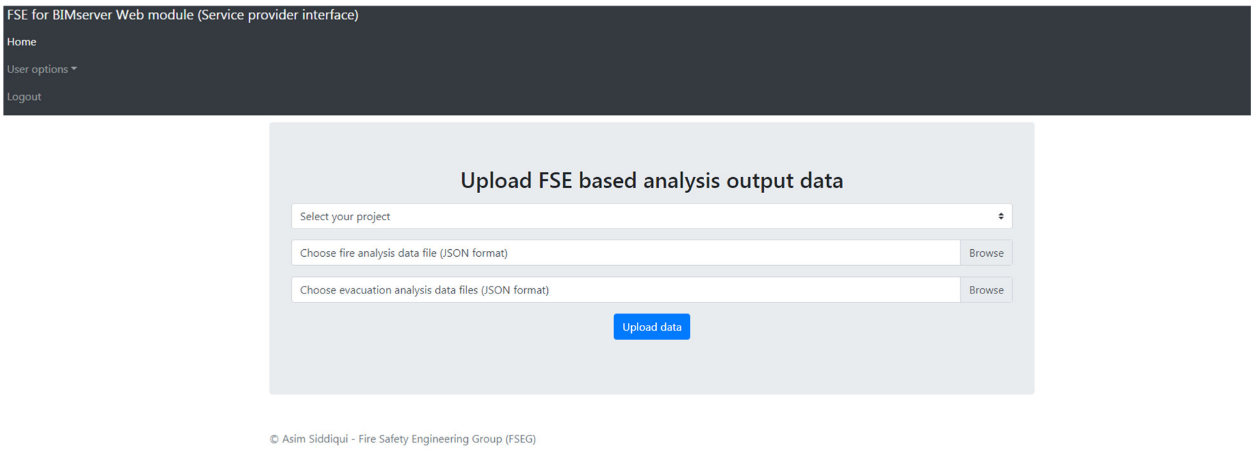

Figure 4.13: Upload analysis data page for FSE for BIMserver Web module (service provider interface)

As an additional step, to assist in ASET and RSET value calculation (CFPA Europe, 2009), queries and code have been written as well. The idea is to run these queries and code once the analysis data has been added to the database. It should be noted that the ASET value can be calculated in various ways as there is no agreed upon method (Galea *et al.*, 2008). Furthermore, the coupled ASET/RSET analysis approach where the impact of fire hazards on the population is taken into consideration, look at the results together (Galea *et al.*, 2008). It should be made clear this research is not advocating using a specific approach and/or how these values should be calculated as that is not an objective of this work. However, it is highlighting that there is a potential where this type of system can be used by adopting a combination of database queries and additional code in facilitating finding these values. More discussion on this is included in Chapter 5.

Note: The prototype system also has an email notification feature which is triggered at relevant events (e.g. on submission of analysis request by the client). Also note that during the development work to establish data sharing between BIM and FSE, some adjustments were made to the FSE based analysis database. The adjustment was mainly the addition of a table called ‘BuildingProjectInfoTbl’ for the purpose of storing references to various items in the BIMserver (e.g. building project and revision). These values are added to the database and checked using various services in the services bundle.

Some points to be noted about the implementation:

- The current version of the IFC import utilities in buildingEXODUS and SMARTFIRE are limited to geometry extraction i.e. other data which may be relevant and available in an IFC file is not imported.
- The IFC specification has the zone concept as mentioned previously in this chapter. The extraction of zone data (if available) has not been implemented in the IFC import utility in SMARTFIRE but adding this option could be part of the future development work.
- Currently, the IDs of objects (e.g. wall and door) in IFC are not retained by the IFC import utilities in buildingEXODUS and SMARTFIRE. This is also part of future improvement work.
- The BIMserver has an online user guide covering the basics but its contents at times can be confusing and conflicting due to different versions and incomplete details. This means, tasks such as upgrading to a newer version of BIMserver can introduce compatibility problems for plugins.

4.5 BIM support enhancements recommendations for fire/evacuation modelling tools

IFC Import enhancements

- Automatic extraction of components such as staircases and lifts to speed up model generation.
- Extraction of *IfcSpace* elements and constructing a connectivity graph from the *IfcRelSpaceBoundary* relationships.
- Automatic extraction of compartment/room connectivity to allow for improved agent navigation.
- Extraction of location data of smoke management components and furniture elements.
- Extraction of material properties in SMARTFIRE.
- Extraction of data in FSE relevant property sets (e.g. *Pset_SpaceFireSafetyRequirements* and *Pset_SpaceOccupancyRequirements*) if available.
- Extraction of zone data (if specified) from an IFC file.
- Currently, the IDs of objects (e.g. walls and doors) in IFC are not retained by the IFC import utilities in buildingEXODUS and SMARTFIRE. For future data sharing with BIM, for accuracy and reference purpose, these IDs should be retained and additionally assigned to the key objects such as exit doors when analysis data is exported.

The output of fire and evacuation generated data in a commonly used format: Currently, the fire data generated by SMARTFIRE is exported in native DAT format while the evacuation generated data by buildingEXODUS is in native SIM format. It is recommended that this data should also be exported in a widely used standard format such as JSON/XML using a structure similar to the one proposed by the prototype database. It is also worth mentioning here that due to the benefits offered by the JSON format, its use for BIM web based data exchange has also been highlighted with the outline implementation of ifcJSON, a JSON serialization of IFC data model (Afsari, Eastman and Castro-Lacouture, 2017).

4.6 An application of BIM with FSE in Smart Building environment

According to Oti *et al.* (2016), the focus has been mostly on the use of BIM during the design phase and there has been a limited effort on the operational phase. Also, an in-depth review of BIM and its application in FM by Pärn, Edwards and Sing (2017), suggested that the automation within the BIM-FM integration process has the potential to make a major impact on the whole building process but that require innovative solutions with far greater collaboration between the industry and academics.

A combination of BIM and FSE in a Smart Building environment can be beneficial particularly during a building's operational phase. For instance, in response to an emergency situation, automated responses such as the closing of fire doors, activating lighting controls, and directing people using dynamic signage (Clevertronics, no date; Evaclite, no date). Research studies such as project ELASSTIC (CORDIS, 2017a) have highlighted the potential benefits of this type of combination. The benefits of real-time data sharing during incidents involving an evacuation modelling tool was demonstrated in the GETAWAY project (CORDIS, 2017b). The key part of the GETAWAY project was the design and development of an Intelligent Active Dynamic Signage System (IADSS) which was evaluated using full scale evacuation trials (Galea, Xie, *et al.*, 2017). The concepts presented by IADSS are in accordance with a Smart Building environment-based system where various subsystems work together to provide a certain level of automation. However, BIM was not part of the IADSS system but considering the potential benefits of digital data flow throughout a building's lifecycle offered by BIM, adding it to IADSS can present a further research opportunity where this combination can be evaluated at a building's operational phase. First, a brief description of the IADSS system which is then followed by the proposed BIM-enabled IADSS.

Intelligent Active Dynamic Signage System (IADSS)

A description of IADSS based on (Galea, Xie, *et al.*, 2017) is covered here for the purpose of clarity.

Main components and subsystems

Fire Detection System: This system interacted with the installed alarms to gather information about the fire hazards such as smoke, heat and toxic gases. It also interacted with the installed dynamic emergency signage. This system was provided by one of the project partners.

People counting system: The CCTV was used to gather population information and determined using the people counting system provided by one of the project partners.

Evacuation Simulation System: A fire library containing a range of pre-simulated fires produced using the SMARTFIRE fire modelling software was created. An intelligent component Decision Engine (DE) was then developed to identify the optimal exit paths. Based on the fire information provided by the Alarm Detection System and the pattern matching algorithm, the DE identified which pre-determined fire from the fire library to use. The population information provided by the people counting system along with the identified pre-determined fire data is loaded in the evacuation modelling tool buildingEXODUS. Several instances of buildingEXODUS were then executed to cater for various pre-determined evacuation strategies for the structure. Using another algorithm, the DE then based on the simulation results, ranked the strategies from best to worst. This was based on factors such as projected fatalities and injuries, distance travelled, etc.

The system developed for IADSS ran in real-time or faster than real-time to ensure the process is completed within the time the Fire Detection System detects a fire and the alarm is activated. Finally, the ranked evacuation strategies were then presented to the human controller who makes the final decision as to which option to employ. Based on the controller's decision, the dynamic signage system was activated indicating to the occupants not only which way they can go to reach safety but also which one to avoid.

BIM-enabled IADSS or simply Smart Signage Management System (SSMS)

To make IADSS BIM-enabled, certain aspects of the prototype system presented in this chapter can be utilised for a conceptual design of the BIM-enabled IADSS or simply Smart Signage Management System (SSMS). The conceptual design of the proposed SSMS is shown in Figure 4.14. The focus here is to highlight conceptually that BIM and FSE combination can be utilised in a Smart Building environment using SSMS shown in Figure 4.14 as an example.

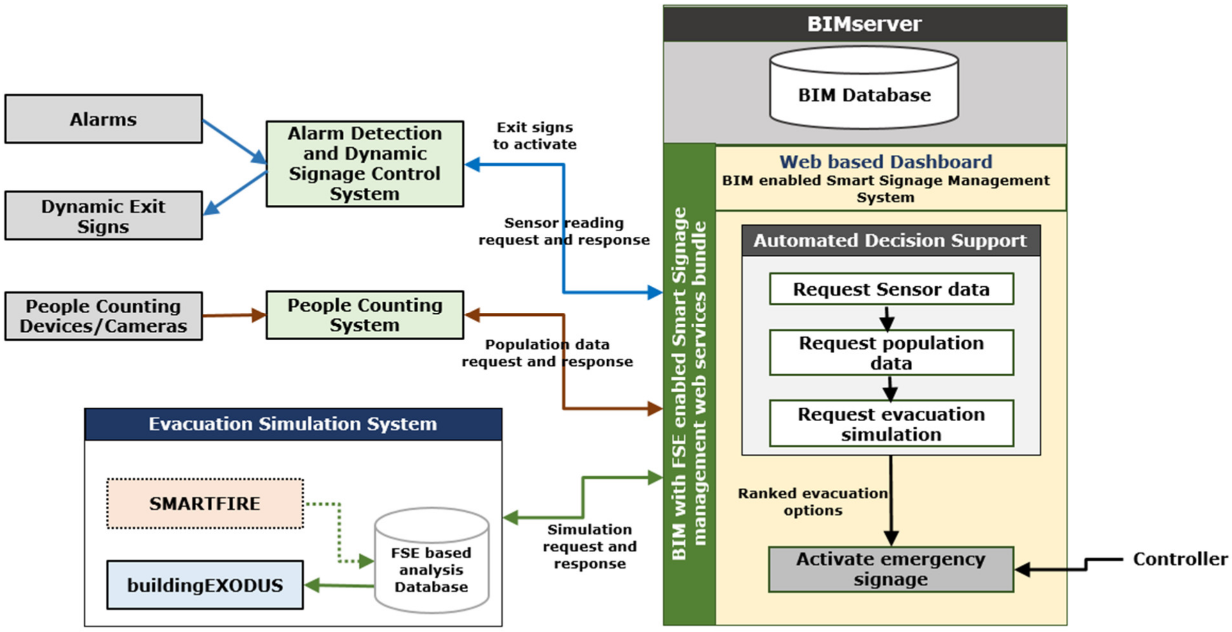

Figure 4.14: Conceptual design of the BIM-enabled Smart Signage Management System

The functionality of IADSS has already been covered and therefore only the BIM related part is mainly discussed here in reference to Figure 4.14.

For a suitable test case building where the proposed SSMS can be employed, the following is assumed: FSE based analysis at the building design phase has already been conducted for each identified fire scenario using the prototype system presented in this chapter. This means the analysis results were captured in the FSE based analysis database and shared with BIM. At the design phase, details of various building elements (Alarms, emergency signs, and people counting devices/cameras) shown in Figure 4.14 has been assumed to be added in BIM as well. For instance, information about alarms can be captured in the IFC Model by Building Controls Domain (*IfcBuildingControlsDomain*) which define concepts of building automation, control, instrumentation and alarm. One key benefit of BIM is that it allows manufacturers to provide accurate details of their products which can then be added as BIM objects. The National BIM Library (NBS, no date) has established an online repository where manufacturers can upload details of their products. These products can then be added as BIM objects to a building design using software such as Revit.

Main components and subsystems

Alarm Detection and Dynamic Signage Control System: This system can be similar to the one used by IADSS. The purpose is to interact with the installed alarms to gather information about the fire hazards such as smoke, heat and toxic gases. Furthermore, this system can also interact with the installed dynamic emergency signage.

People counting devices/cameras and the People Counting System: There are a number of ways this information can be collected (Farah, 2018). For instance, using people counting devices (*TD-2000 3D Intelligent Sensor – TDI*, no date; IEE, no date) or cameras, population information such as number and distribution can be collected.

Evacuation Simulation System: The main concepts of this system can be similar to IADSS. However, for SSMS, the following changes are proposed:

- Web-based Dashboard for interacting with various subsystems using BIMserver based web services bundle. The web-based frontend connected with the backend system through web services approach adopted for the prototype system, presented in this chapter, can be utilised. This integrated system, by interacting with all the subsystems using the web services, can provide the required functionality. The web services bundle can include several sub-bundles covering various subsystems (Population data services bundle, Alarm and emergency signage data services bundle, Evacuation simulation services bundle, and Emergency Signage System services bundle). These bundles work together as part of an Automated Decision Support. The human controller, through the Dashboard, can access a list of ranked evacuation strategies provided by the Automated Decision Support.

Even though the proposed system uses a web-based approach, it can be setup so that it is not accessible externally for security reasons. It can be optimised to perform according to the requirements. Also, for data storage purpose, a high-performance DBMS for storing FSE based analysis data can be used.

An important benefit of this BIM-enabled system is that once a fire emergency event has ended, the generated evacuation data can then be added to the FSE based analysis database. As the database already has all the data from the design phase scenarios, adding the new data will not only provide data from an actual event but it can also be compared with existing data for further analysis.

Another point worth mentioning here related to building automation systems is that the *IfcBuildingControlsDomain* schema of the IFC Model does not specify building automation protocols. However, mapping to standard protocols or vendor implementations is possible. Furthermore, there is also an *IfcPerformanceHistory* entity which is used for capturing a real-time device state of control elements. The idea is to document actual performance over time that includes both the machine measured data from building automation systems and also human specified data representing the actual condition, predictions or simulations (buildingSMART, 2016b). This is useful for real-time monitoring and measurement, for instance for sensors (Edmondson *et al.*, 2018).

The conceptual design with a description of the proposed SSMS has been provided. However, the implementation of this system was beyond the scope of this study due to time constraints and requirements of significant practical resources.

4.7 Concluding remarks

The development work in support of the three-step strategy for BIM with FSE data sharing and proof of concept system to demonstrate that was discussed in this chapter. To support the strategy, the data requirements for FSE were first analysed that can lead to the development of an MVD for FSE as part of the project proposal to buildingSMART. Based on the data requirements analysis, a database schema capturing this data was then presented. The implementation of this database schema in a suitable DBMS was also included. The development work by the FSEG in parallel to this research on adding IFC import capabilities in fire and evacuation modelling tools SMARTFIRE and buildingEXODUS was also discussed. Even though the author did not work on the IFC import development work, the findings and recommendations of this research were communicated to the FSEG who are working on enhancing buildingEXODUS and SMARTFIRE capabilities in support of BIM.

The design and implementation of a proof of concept system to demonstrate the data sharing between BIM and FSE was covered. For this system, the web services bundle was implemented in Java programming Language for the BIMserver (an open source platform for BIM data).

Furthermore, a Web frontend was developed to demonstrate certain aspects of data sharing. A combination of some existing tools and newly developed ones, the data sharing between BIM and FSE was successfully established. Although there are some limitations, the main aspects of data sharing were tested with suitable case studies, as covered in Chapter 5.

Finally, a conceptual design of BIM-enabled Smart Signage Management System was presented as an example application of future BIM with FSE data sharing in a Smart Building environment during the operational phase of the building lifecycle. Due to time constraints and requirements of significant practical resources, it was not possible to implement and test this proposed system as part of this project.

5 CASE STUDIES AND TESTING

In this chapter, the testing of the proof of concept system described in Chapter 4, using two selected case studies, one for the design phase and the other one for fire incident forensic analysis, are covered. The four main steps (1. Client submits FSE based analysis request to the service provider, 2. Service provider acquires the input data, 3. Service provider upload analysis data to the analysis database, and 4. Client query the analysis data) of the prototype system used for demonstrating two way data flow between BIM and FSE were tested using two selected case studies in this chapter.

5.1 Selected case studies

The data sharing between BIM and FSE based analysis using fire and evacuation modelling tools has benefits as stated in Chapter 3 at various phases of building lifecycle including design, design change, operational and even for post fire incident forensic analysis study. To test the prototype system to demonstrate the data sharing between BIM and FSE using buildingEXODUS and SMARTFIRE as representative evacuation and fire modelling tools, two test case studies were used. One of these case studies was used for testing the data sharing between BIM and FSE at the building design phase while the other one for post fire incident forensic analysis.

The first case study selected for design phase testing of data sharing between BIM and FSE is a Day Care Facility while the second one is Rhode Island Station Nightclub fire for forensic analysis. These case studies were selected because they offered a suitable level of complexity including scenarios for the purpose of testing data sharing between BIM and FSE.

5.1.1 Day Care Facility case study

This is a fictitious Day Care Facility for senior citizens consisting of two identical floors. It has one main exit and three emergency exits, all located on the ground floor. Also, the floors are linked by two staircases. The facility has several nursing rooms, communal areas and offices for the members of staff. The population characteristics and assumptions are mentioned below:

- There are 150 people aged 65 to 90 of mixed abilities (for mobility) within the facility and four staff members. The ground floor has 100 occupants and the top floor has 50 occupants. Two staff are located on the ground floor and two staff on the first floor. Also, occupants are not located in the corridors, landings or staircases.
- Fast walk speed of all occupants is between 0.9m/s and 1.3m/s.
- Three types of occupants are present in the structure: able-bodied response time 60s – 180s, non-able-bodied response time 150s – 240s, and staff response time 60s.
- Able-bodied population represents 90% and non-able-bodied 10% of the population. The able-bodied population consists of 50% males and 50% females. The non-able-bodied population consists of 60% (~66% male, ~33% female) that need no aid to move and 40% (50% male, 50% female) that require a walking stick to walk.

Important note: This case study and the analysis work was part of FSEG's internal project which the author was not part of.

To demonstrate the data sharing between BIM and FSE, a BIM model of this facility was needed considering the existing one was in CAD format. Therefore, a BIM model of the facility was created in Revit 2018, see Figure 5.1.

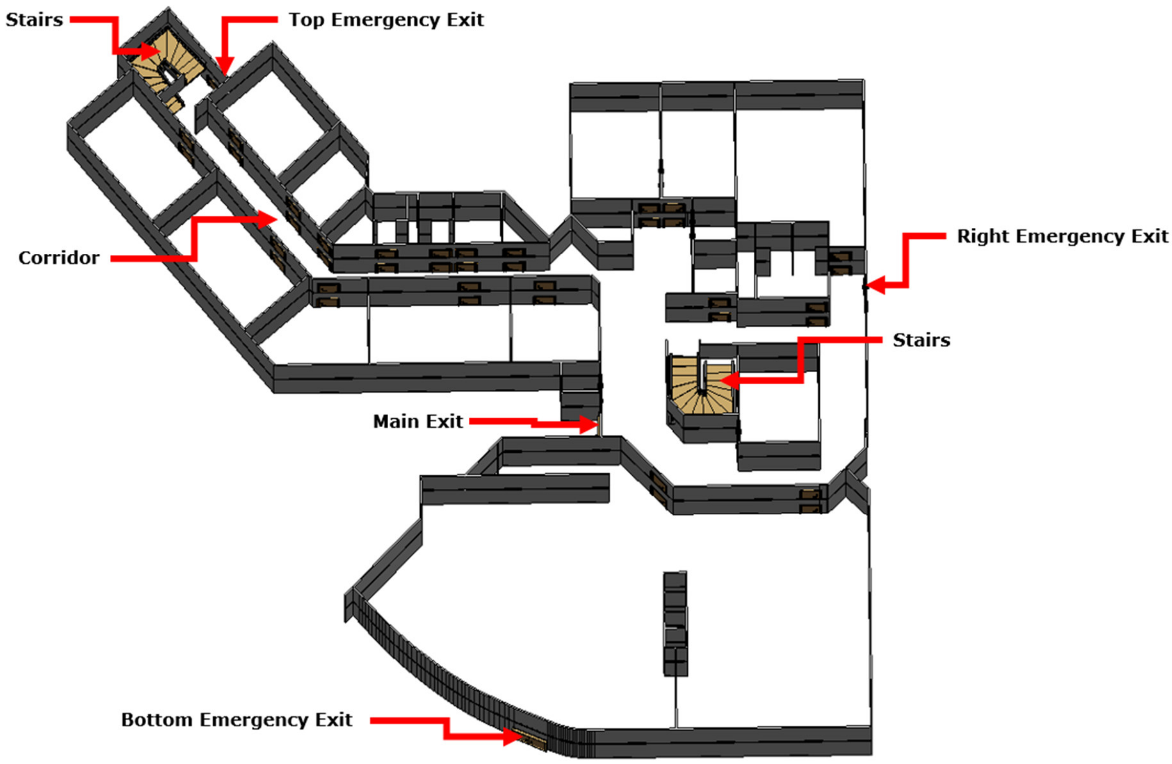

Figure 5.1: Day Care Facility BIM model in Revit

5.1.2 Rhode Island Station Nightclub case study

The Station Nightclub fire which took place on 20 February 2003 in West Warwick, Rhode Island, killed 100 people while 230 were injured. The NIST conducted a full scale reconstruction of the stage fire for the Station Nightclub incident (Grosshandler *et al.*, 2005). It should be noted that the experiment provided additional validation of the simulation – which would not be available from the real incident. The study by the FSEG, simulated the Station Nightclub fire using SMARTFIRE and buildingEXODUS (Galea *et al.*, 2008). The following are some assumptions regarding the population characteristics:

- The population of the Nightclub at the time of the incident was 460 (259 Male and 201 female) and most of them were situated on or around the dance floor. Approximately 21 people were also distributed in the storage, office, restrooms and dressing room areas.
- The population density varied from 2.8 persons/m^2 on the dance floor to 0.72 persons/m^2 in the bar area.

The forensic analysis of this case study conducted by FSEG used CAD approach. For this case study, a BIM model was needed and therefore it was created by the author using Revit 2018, see Figure 5.2. A point worth mentioning here, as it relates to BIM IFC format, is that even though a 3D model of the Station Nightclub in Google SketchUp was available (W, 2015), the exported IFC file does not comply with the IFC schema in accordance with buildingSMART (SketchUp, 2018). All the building elements (e.g. Walls and doors) were simply exported as 'Building Element Proxy'. This highlights that simply exporting to IFC format without preserving the elements and their properties will result in loss of essential data.

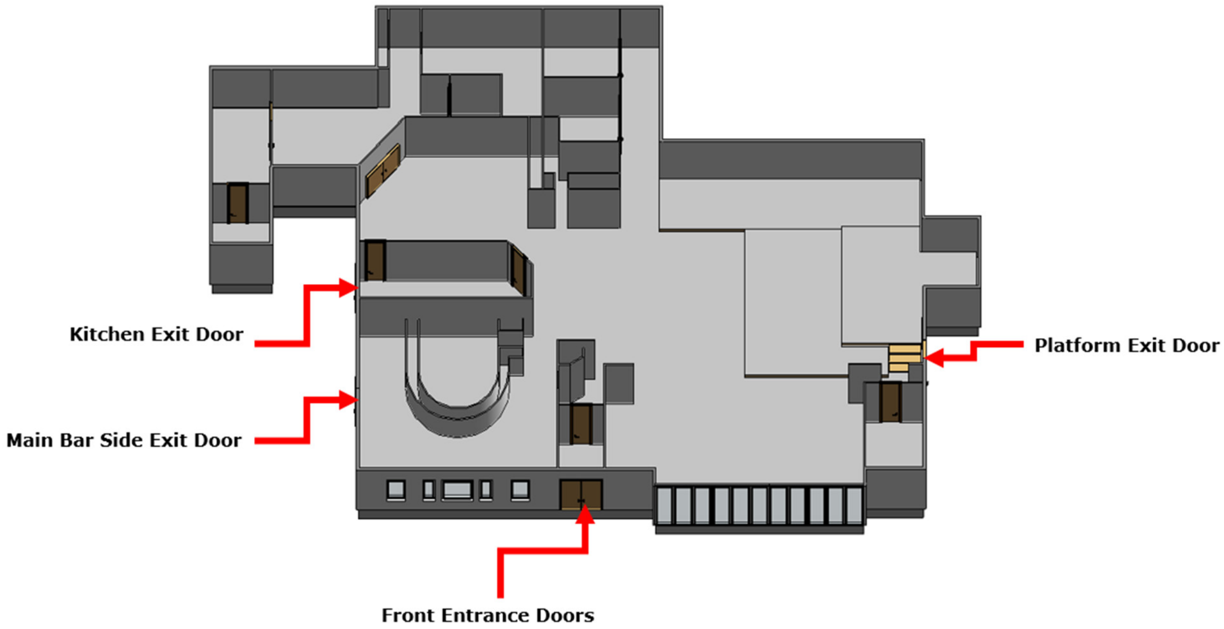

Figure 5.2: Station Nightclub model in Revit

5.2 Workflow for testing

By using the Day Care Facility and the Station Nightclub case studies, the data sharing process between BIM and the fire and evacuation modelling tools was demonstrated, enabled by the BIMserver and the prototype system mentioned in Chapter 4, for the design phase and post incident forensic analysis. This demonstrated two-way data flow between BIM and FSE through four main steps of the prototype system i.e. (1) Client submits FSE based analysis request to the service provider, (2) Service provider acquires the input data, (3) Service provider uploads analysis data to the analysis database, and (4) Client query the analysis data. To test these four main steps, the following workflow consisting of a series of tasks was utilised, see Table 5.1.

Table 5.1: Workflow for selected case studies for BIM with FSE

Main tasks	Subtasks
Make BIM data available	1. Client exports the BIM model of the case study in IFC format from the BIM design tool it was created in. 2. Client creates a project in BIMserver for the same case study and checks-in the IFC file. 3. Client attaches the essential services and access account to the project. 4. From the web module client submits FSE based analysis (ASET, RSET, or coupled ASET/RSET) request to the service provider.
Acquire BIM data	5. From the web module, service provider downloads the IFC file which can then be imported in the fire and evacuation modelling tool(s). 6. Import IFC file in fire and evacuation modelling tool. If there is a design change which requires fire and evacuation reanalysis then import the updated IFC file in fire and evacuation modelling tool.
Conduct fire and evacuation analysis	7. Setup and run the simulations for the identified scenarios. Depending on the user requirement, the analysis could be ASET, RSET, or coupled ASET/RSET.
Share analysis simulation results with BIM	8. Export the fire and evacuation modelling generated simulation data for all the selected scenarios to the fire and evacuation analysis database. 9. Using the created web services, the service provider adds the key results data from the fire and evacuation analysis database to the BIMserver as extended data. The extended data concept was described in Chapter 4.

Main tasks	Subtasks
View/Query analysis data	10. From the web module, the client runs queries on the conducted fire and evacuation analysis data.

5.3 Testing setup and outcome

The workflow mentioned in the previous subsection was followed for this testing using the two selected case studies.

5.3.1 Day Care Facility case study

Make BIM data available

1. *Client exports the BIM model of the case study in IFC format from the BIM design tool it was created in:* The 3D model of the Day Care Facility was created in Revit 2018 and it is shown in Figure 5.1. This model was exported in IFC format using the ‘Export ->IFC’ option in Revit 2018. There are several IFC version options when exporting so the one used was ‘IFC 2x3 Coordination View 2.0’. This version is the default certified version of export and the latest version generally supported by other systems, based on the IFC 2x3 schema and the Coordination View 2.0 model view definition (Autodesk, 2018).

A freeware IFC Model viewer tool called BIM Vision (BIMVision, no date) can be used to view the exported IFC. Even though this is not part of this first step, the BIM Vision does offer model visualisation options which do highlight how well the model has been exported in IFC format. Just as an example, the Day Care Facility IFC file opened in BIM Vision is shown in Figure 5.3.

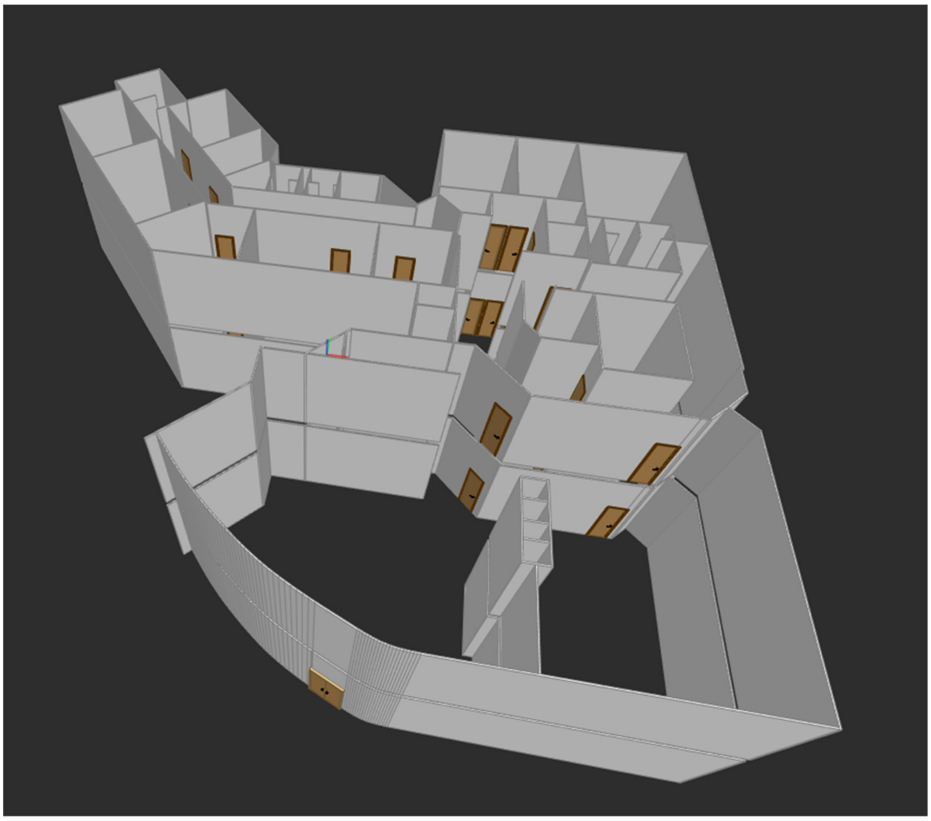

Figure 5.3: Day Care Facility IFC file opened in BIM Vision IFC Model viewer

2. *Client creates a project in BIMserver for the same case study and checks-in the IFC file:* The BIMserver uses an open source web module called bimvie.ws (Bimvie, no date) which is a software tool to view and evaluate BIM models online. The bimvie.ws is compliant with the BIM Service interface exchange BIMSie standard API (*BIMsie API*, no date) for BIM in the cloud. It provides an admin web frontend to BIMserver. By using bimvie.ws, it is possible to achieve the requirements of this step i.e. creating a project and check-in IFC for the project. Using the admin account, a project called 'Day Care Facility' was created in BIMserver through the bimvie.ws frontend. The IFC file which was exported from Revit was then imported for this project using the check-in option. See Figure 5.4.

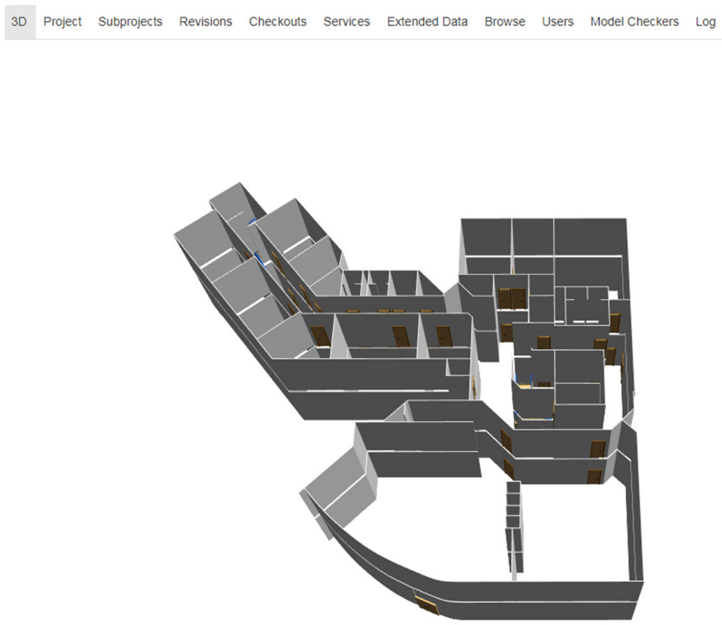

Figure 5.4: Day Care Facility project in BIMserver

3. *Client attaches the essential services and access account to the project:* A plugin bundle called 'FSE plugins for BIMserver' has been created to demonstrate various data sharing aspects between BIM and fire and evacuation modelling tools, as explained in Chapter 4. After creating a project for the Day Care Facility in the BIMserver, some essential services including the above-mentioned plugin bundle were attached using bimvie.ws. To make it easier to demonstrate the fire and evacuation analysis data sharing functionality between BIM and the fire and evacuation modelling tools, a web module called 'FSE for BIMserver' was developed as well and mentioned in Chapter 4. This web module is listed along with other web modules on the default BIMserver page.
4. *From the web module client submits FSE based analysis (ASET, RSET, or coupled ASET/REST) request to the service provider:* Using the FSE for BIMserver web module, a client can submit a fire and evacuation analysis request to the service provider. This step adds the request for analysis in the fire and evacuation analysis database which has been created for the Day Care Facility along with an essential reference to the project in BIMserver. Also, the request and initial automated response are attached to the BIMserver as extended data. The benefit of this step is that it establishes an audit trail of BIMserver and FSE communication. Usually, the client and the service provider would have already agreed to conduct this analysis and have a contract in place which means the analysis request and the type of analysis would have been recorded somewhere by both the client and the service provider. However, this step

was added primarily for creating a reference between the BIMserver and the FSE based analysis database. Furthermore, this step adds clarity and improves communication. See Figure 5.5.

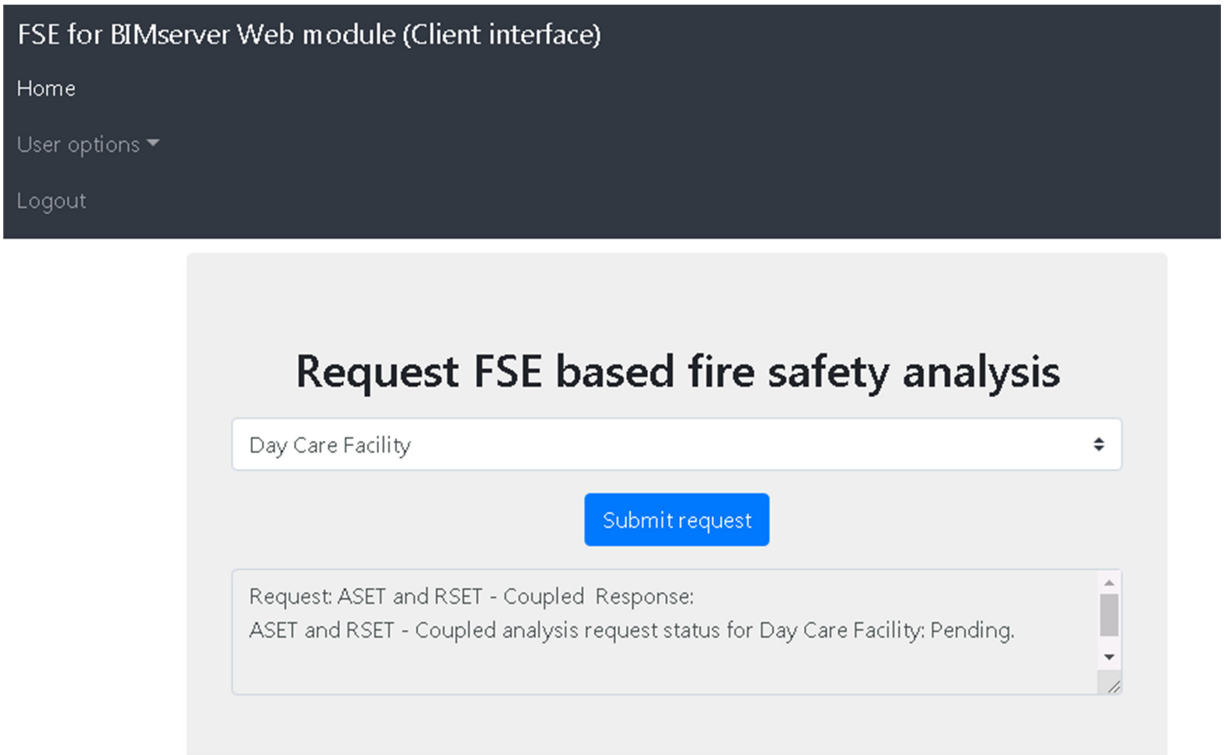

Figure 5.5: Submit a request for fire and evacuation analysis

<u>Acquire BIM data</u>

5. *<u>From the web module, service provider downloads the IFC file which can then be imported in fire and evacuation modelling tool:</u>* At the end of the previous step, the client has setup a project for the Day Care Facility in the BIMserver, attached essential services to it and submitted a request for fire and evacuation analysis. Now using the FSE for BIMserver web module, the service provider can login to the BIMserver and acquire the BIM data by downloading the IFC file. See Figure 5.6.

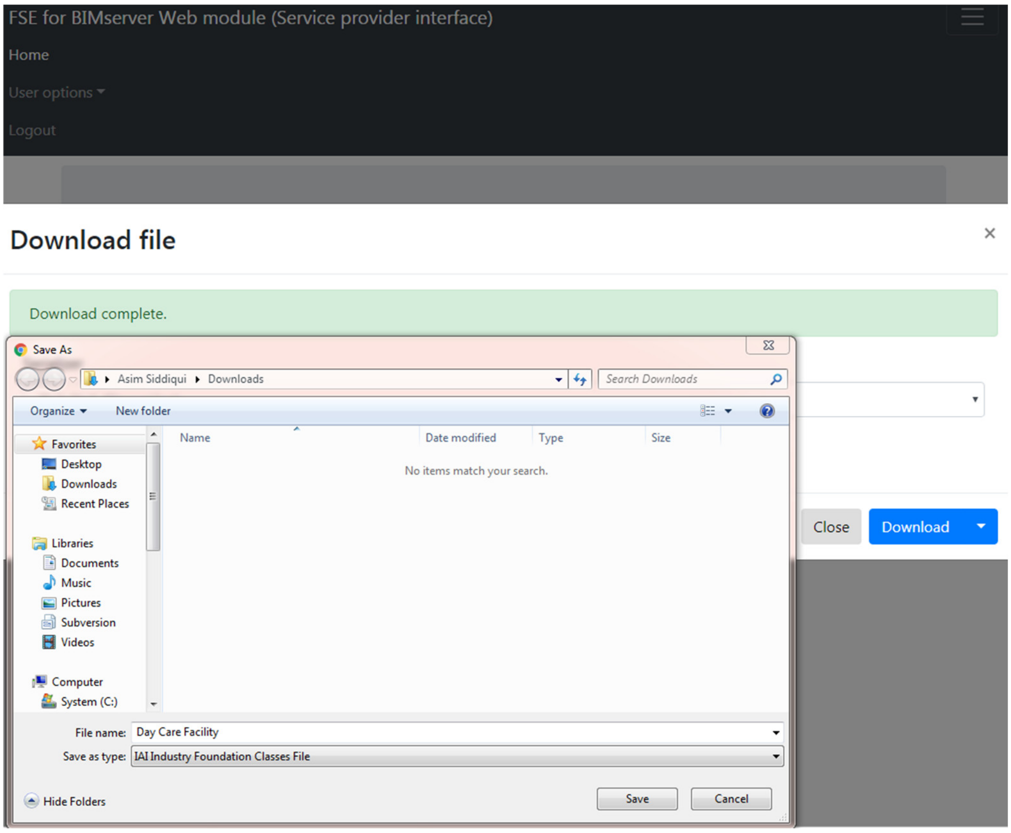

Figure 5.6: Download Day Care Facility IFC file

Note: The IFC download functionality was adapted from a bimvie.ws feature with some modifications.

6. *Import IFC file in fire and evacuation modelling tool:* Refer to the Input data Table 4.3 in Chapter 4 for details of what type of data can be acquired from an IFC file. The information about the scenarios identified for fire and evacuation analysis is covered in the next step i.e. Conduct fire and evacuation analysis. For the purpose of clarification, it is best to go through the above in conjunction with this step.

The IFC import utility for buildingEXODUS is available as part of the released version but for SMARTFIRE a utility is currently being developed for the next release. However, a command line version is currently available for FSEG's internal research use. Using the command line import utility, the IFC file of the Day Care Facility was successfully imported in SMARTFIRE as shown in Figure 5.7.

Figure 5.7: Day Care Facility IFC file imported in SMARTFIRE

Similarly, the IFC file of the Day Care Facility was successfully imported in buildingEXODUS using the default options and is shown in Figure 5.8.

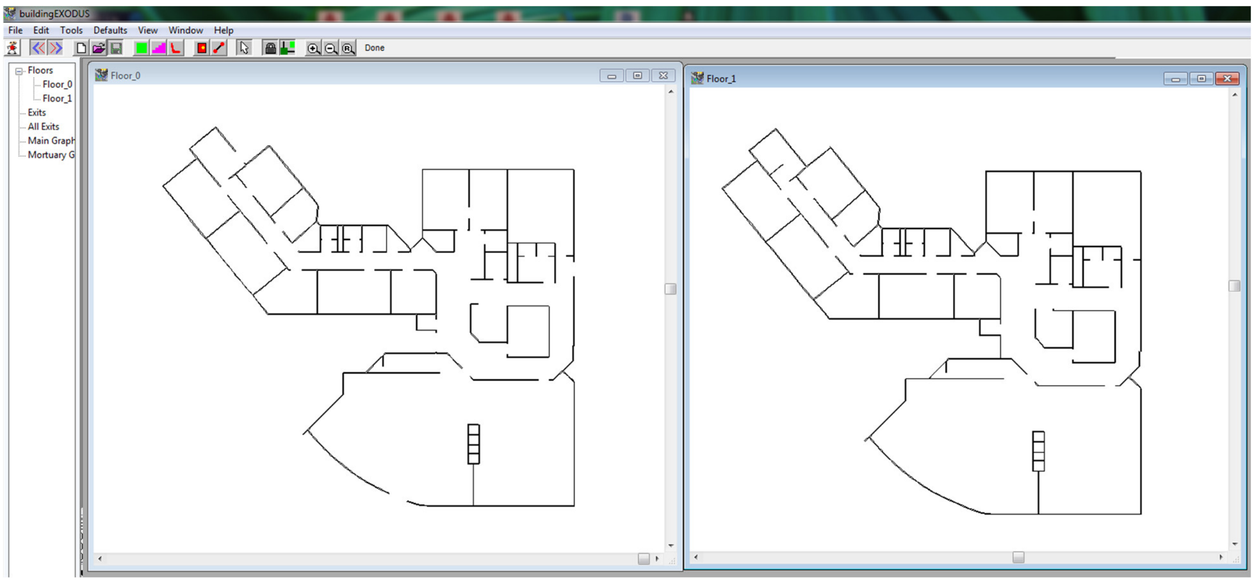

Figure 5.8: Day Care Facility IFC file imported in buildingEXODUS

Note: In the future, there is a possibility of somewhat automating this process which can be achieved by creating a script that can invoke buildingEXODUS and SMARTFIRE, send them the IFC file to import and get a response from them. This can serve as an initial confirmation that the IFC file provided by the client can be imported before proceeding with the next steps.

Conduct fire and evacuation analysis

7. *Setup and run the simulations for the identified scenarios:* At the end of the last step, it was established that the Day Care Facility IFC file import process successfully worked for both SMARTFIRE and buildingEXODUS.

The analysis work was not undertaken by the author but instead, it was part of FSEG's internal project. Four scenarios (A base case scenario, two fire mitigation scenarios and one base case structural and procedural modification scenario) were identified and modelled in SMARTFIRE for fire analysis and buildingEXODUS for the evacuation analysis using coupled fire and evacuation analysis approach. The identified scenarios are suitable for highlighting the impact of adjustments (e.g. smoke management alterations and structural modifications) that can have an impact on the fire safety aspects. A description of the four scenarios is covered below:

Scenario 1 (Base case scenario): This represents the base case fire scenario where fire propagates with no mitigation/suppression measures. The facility is subject to an arson fire which can result in multiple fatalities. An arson fire starts on the ground floor, just beneath the stairs at the end of the corridor. The fire effluents propagate to the rest of the ground floor and via the staircases to the first floor. Some nursing rooms on the ground and first floors are protected by fire doors, therefore the fire products do not propagate within those areas. The severity of the fire is such that it can cause a high number of fatalities and injuries unless appropriate measures are taken.

Scenario 2 (Fire mitigation alteration): To investigate the potential improvement (or worsening) of the conditions in the Day Care Facility due to using a given set of smoke-management alterations (two smoke extract shafts located on the upper floor, one located at the west end of the main corridor and another at the main hall), this fire mitigation scenario was identified as it can impact on the evolution of the fire hazard environment. The following should be noted: 1) A fire door at the top of the left stair core is closed – sealing this stair core from the upper corridor, 2) A smoke extract shaft at the top of the left stair core in the upper storey, 3) A smoke extract shaft in the large room of the upper storey. In this scenario, two fans are active on the upper floor.

Scenario 3 (Fire mitigation alteration): Like Scenario 2, this fire mitigation scenario was identified as it can impact on the evolution of the fire hazard environment. For this scenario, the following applies as well: 1) A fire door at the top of the left stair core is closed – sealing this stair core from the upper corridor, 2) A smoke extract shaft at the top of the left stair core in the upper storey, 3) A smoke extract shaft in the large room of the upper storey. In this scenario, one fire door at the top of the left-hand stair core and one smoke extract shaft located on the upper floor, are active. Although there is also a door present at the top of the second stair core – this is assumed to be wedged open.

Scenario 4 (Procedural and structural modifications): This is base case fire scenario with some procedural and structural modifications to the Day Care Facility that can impact on the survivability of the occupants. The main structural modification is that pass doors are added to the rooms along either side of the corridor on both the ground and first floors. This is to enable occupants to exit these rooms with only limited interaction with the corridor and its hazardous conditions. In addition to that, some procedural changes such as staff response times have been made.

All the required data to setup and run simulations was acquired at the previous step. At this step, selected fire and evacuation modelling tools SMARTFIRE and buildingEXODUS were prepared to run the simulation for the identified scenarios. Separate fire simulations were run for the first three scenarios in SMARTFIRE. For evacuation analysis in buildingEXODUS, 10 simulations (EXODUS is stochastic in nature hence the user needs to run several simulations to find a distribution of results) were run for each scenario. For Scenario 4, fire data generated by SMARTFIRE for Scenario 1 was used for evacuation analysis in buildingEXODUS.

<u>The original/initial design of the Day Care Facility (Scenario 1)</u>: First, based on the analysis in SMARTFIRE, the simulated fire data was generated and made available to use in buildingEXODUS to cater for the impact of fire hazards on the population. It should be noted that the geometry was simplified in SMARTFIRE by replacing the upper left angled corridor with a straightened long corridor because the Fire Engineer decided to straighten the angled corridor so that the geometry was compatible with the fire modelling environment. This change was deemed to have no significant impact on the nature or quality of the results. See Figure 5.9.

Figure 5.9: Simplified Floor Plan for the Day Care Facility in SMARTFIRE

In buildingEXODUS, the fire data was loaded, and 10 simulations were run. The main outcome of the simulations is that there were fatalities (average 13) for Scenario 1.

<u>Modifications to the design of the Day Care Facility</u>: Same as for Scenario 1, other scenarios i.e. 2, 3 and 4 were analysed using the coupled fire and evacuation approach. For the fire mitigation Scenarios 2 and 3, some smoke extract shafts were added to the building geometry within SMARTFIRE to investigate the potential improvement (or worsening) of the conditions in the Day Care Facility. In case of Scenario 2, the following should be noted: (1) A fire door (FIRE DOOR 1) at the top of left stair core is closed – sealing this stair core from the upper corridor, (2) A smoke extract shaft (SMOKE SHAFT C) at the top of the left stair core in the upper storey, and (3) A smoke extract shaft (SMOKE SHAFT E) in the large room of the upper storey. Two Fans Active on Upper Floor: In this scenario, only Smoke Extract Shaft C and Smoke Extract Shaft E are active. See Figure 5.10 (provided by FSEG).

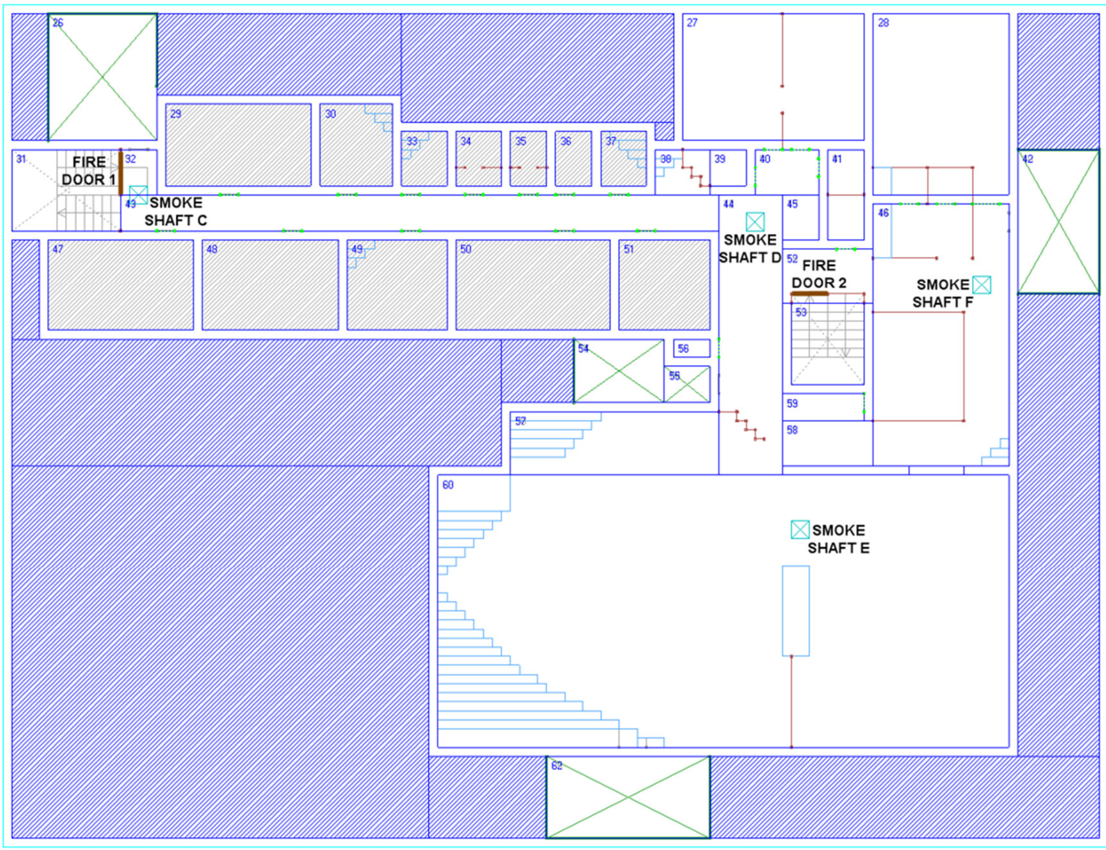

Figure 5.10: Day Care Facility in SMARTFIRE - fire doors and smoke extraction shown

First based on the analysis in SMARTFIRE, the simulated fire data for Scenario 2 was generated and made available to use in buildingEXODUS to cater for the impact of fire hazards on the population. In buildingEXODUS, the fire data for Scenario 2 was loaded and 10 simulations were run. The main outcome of the simulations is that the fatalities (average 11) still occurred even though fire mitigation was introduced in Scenario 2.

In case of Scenario 3, as in Scenario 2, fire mitigation changes were added to the building geometry within SMARTFIRE to investigate the potential improvement (or worsening) of the conditions in the Day Care Facility. The following applies for this scenario: (1) A fire door (FIRE DOOR 1) at the top of left stair core is closed – sealing this stair core from the upper corridor, (2) A smoke extract shaft (SMOKE SHAFT C) at the top of the left stair core in the upper storey, and (3) A smoke extract shaft (SMOKE SHAFT E) in the large room of the upper storey. One Fire Door and One Fan Active on Upper Floor: In this scenario, Fire Door 1 at the top of the left hand stair core and Smoke Extract Shaft C located on the upper floor are active (see Figure 5.10). Although there is also a door present at the top of the second stair core – this is assumed to be wedged open.

Based on the analysis in SMARTFIRE, the simulated fire data for Scenario 3 was generated and made available to use in buildingEXODUS to cater for the impact on fire hazards on the population. In buildingEXODUS, the fire data for Scenario 3 was loaded and 10 simulations were run. The main outcome of the simulations is that, although fire mitigation was introduced, there were a higher number of fatalities (average 38) for Scenario 3.

For Scenario 4, geometry modifications were made in buildingEXODUS to cater for the pass doors on both floors. The fire data for Scenario 1 generated by SMARTFIRE was used in buildingEXODUS for this as well, see Figure 5.11.

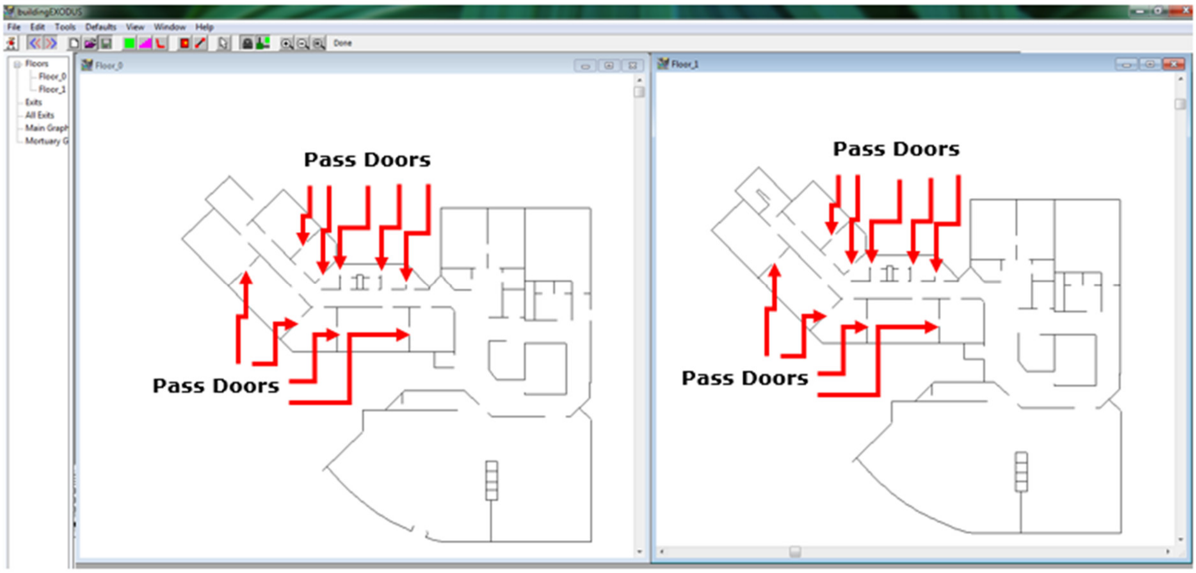

Figure 5.11: Scenario 4 for Day Care Facility – Pass doors added in buildingEXODUS

In buildingEXODUS, 10 simulations were run for Scenario 4 as well. The main outcome of the simulations is that there were no fatalities for Scenario 4. This Scenario represents the acceptable solution and therefore the client must be informed about the recommended design changes.

<u>Share analysis simulation results with BIM</u>

8. *<u>Export the fire and evacuation modelling generated simulation data for all the scenarios to the fire and evacuation analysis database:</u>* Once the analysis work has been completed, the simulated generated data needs to be exported to the fire and evacuation analysis database. First, the following is a brief description of SMARTFIRE and buildingEXODUS generated simulation files:

Based on the SMARTFIRE manual (Ewer *et al.*, 2013), the following points should be noted about the SMARTFIRE generated fire hazard data file which is in DAT format and very similar to the CFAST data export file. A hazard sub-volume (or zone) approach that processes the numerical field data produced by SMARTFIRE is used that allows a sub-volume summary form of that data to be loaded into buildingEXODUS. The hazard sub-volume data is generated at each time-step within the SMARTFIRE simulation. The buildingEXODUS uses a sub-volume (or zonal) approach for the specification of hazard information. Also, the hazard information is only required at two characteristic heights (head height and crawl height).

It should be noted that the smoke zone height information which may be required by some other packages, is not included. However, the SMARTFIRE data file format is capable of storing it. In fact, it is trivial to add smoke layer height back into the output file, but it is not always clear how this should be calculated accurately for an extensive CFD based zone that has a complex layering or dispersion of smoke. This concept only really works for the simpler Zone model (Ewer *et al.*, 2013). As an example, an extract of the DAT file which was generated for Scenario 1 is shown in Figure 5.12.

```
  8   70
temp
smoke
hcl
rad
co2
co
o2
hcn
    1       0.000   2.88152e+002   2.88152e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    2       0.000   2.88149e+002   2.88148e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    3       0.000   2.88153e+002   2.88149e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    4       0.000   2.88147e+002   2.88153e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    5       0.000   2.88150e+002   2.88151e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    6       0.000   2.88150e+002   2.88150e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    7       0.000   2.88150e+002   2.88150e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    8       0.000   2.88150e+002   2.88150e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
    9       0.000   2.88150e+002   2.88150e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
   10       0.000   2.88154e+002   2.88152e+002   0.00000e+000   0.00000e+000   0.00000e+000   0.00000e+000
```

Figure 5.12: An extract of the SMARTFIRE generated fire data DAT file

The following can be noted about the DAT file extract shown in Figure 5.12:

- In the first row, the top left value which is 8 represents the types of fire hazards.
- The second value after 8 in row one is 70 which represents the number of sub regions (zones).

- In rows two to nine, the fire hazard types are listed.
- After row nine, for each zone at the stated time interval (in this case, only 10 zones for the time interval 0.000), upper and lower data values of each fire hazard type (in this case, only the upper and lower values of the first three fire hazard types) are shown.

In case of buildingEXODUS, simulation data is in SIM extension files. As an example, an extract of data from one of the SIM files of Scenario 1 is shown in Figure 5.13.

```
Number of People out 141, first out (secs) 65.96  last 331.41

Final Simulation time 331.41 (s)

Number of People Starting on floor 0 (GroundFloor) was 102, last exit (secs) 331.41
Number of People Starting on floor 1 (FirstFloor) was 52, last exit (secs) 275.84
Number of deaths 13, first (secs) 95.97  last 246.12

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Egress Results:-

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  Pos|Gender      |Start Node  |Level|Floor       |  Age|      Weight (kg)|Mobility|Response (s)|End Node     | CWT (s)|Dista
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    1|Male        |1546        |    0|GroundFloor |   25|            80.00|    1.00|       60.00|Main         |    0.00|
    2|Male        |967         |    0|GroundFloor |   25|            80.00|    1.00|       60.00|Main         |    0.00|
    3|Male        |1467        |    0|GroundFloor |   73|            48.28|    1.00|       65.19|Right_Emergency|    0.00|
    4|Male        |1568        |    0|GroundFloor |   74|            79.83|    1.00|       65.33|Right_Emergency|    0.00|
    5|Female      |1199        |    0|GroundFloor |   75|            75.36|    1.00|       72.10|Main         |    0.00|
    6|Male        |3990        |    1|FirstFloor  |   25|            80.00|    1.00|       60.00|Main         |    0.00|
    7|Male        |2840        |    0|GroundFloor |   77|            85.37|    1.00|       66.09|Right_Emergency|    0.00|
    8|Female      |2912        |    0|GroundFloor |   71|            81.78|    1.00|       76.16|Bottom_Emergency|    0.00|
    9|Female      |2433        |    0|GroundFloor |   81|            40.51|    1.00|       72.90|Bottom_Emergency|    0.00|
   10|Male        |4629        |    1|FirstFloor  |   25|            80.00|    1.00|       60.00|Main         |    0.00|
   11|Male        |2530        |    0|GroundFloor |   72|            58.57|    1.00|       70.25|Right_Emergency|    0.00|
   12|Female      |1652        |    0|GroundFloor |   90|            42.28|    0.99|       75.28|Main         |    0.00|
   13|Female      |2897        |    0|GroundFloor |   79|            52.42|    1.00|       71.52|Right_Emergency|    0.00|
   14|Female      |1078        |    0|GroundFloor |   81|            50.95|    0.94|       70.16|Main         |    0.00|
   15|Female      |2031        |    0|GroundFloor |   75|            60.57|    1.00|       82.13|Right_Emergency|    0.00|
```

Figure 5.13: An extract from the buildingEXODUS generated SIM file

For this testing, a summary is mentioned below of the data export process covering the main steps:

Open the DAT file containing fire data for the scenario generated by SMARTFIRE and copy the data. The structure of the DAT file is shown in Figure 5.12.

- Paste the data in MS Excel and change its structure due to the database structure requirements. To facilitate this, a macro in MS Excel was created.
- Copy the data in MS Excel to be pasted in the database.
- As mentioned previously, for each scenario, 10 simulations were run in buildingEXODUS which generated 10 SIM files. For each SIM file, key selected data was copied to MS Excel and adjusted based on the database structure requirements. The data was then copied from MS Excel and pasted in the database.

Note: As part of the future work, this manual copy approach will be replaced by an automated process. This will be done by first converting the fire and evacuation simulation data in DAT and SIM files format to a more commonly used standard format (e.g. XML or JSON). By using a script, data will be read, copied and added to the database. Also, to make sure the link between various key objects in BIM (e.g. Doors and Walls) and how they are represented in buildingEXODUS/SMARTFIRE is intact, the ids of these objects in BIM will be added in the database.

Figure 5.14 and Figure 5.15 show data extracts pasted in the database from the DAT and SIM files for the Day Care Facility.

HazardTypeID	HazardTypeName	HazardTypeDescription
1	temp	Temperature
2	smoke	Smoke
3	hcl	Hydrochloric acid
4	rad	Radiation
5	co2	Carbon dioxide
6	co	Carbon monoxide
7	o2	Oxygen
8	hcn	Hydrogen cyanide

FireEvacZoneID	TimeInterval	HazardType	UpperValue	LowerValue	FireSimID
1	0	1	2.88152E+02	2.88152E+02	1
1	0	2	0.00000E+00	0.00000E+00	1
1	0	3	0.00000E+00	0.00000E+00	1
1	0	4	0.00000E+00	0.00000E+00	1
1	0	5	0.00000E+00	0.00000E+00	1
1	0	6	0.00000E+00	0.00000E+00	1
1	0	7	2.08437E+01	2.08437E+01	1
1	0	8	0.00000E+00	0.00000E+00	1
1	2	1	2.88152E+02	2.88152E+02	1
1	2	2	0.00000E+00	0.00000E+00	1
1	2	3	0.00000E+00	0.00000E+00	1
1	2	4	3.90737E+02	3.90793E+02	1
1	2	5	0.00000E+00	0.00000E+00	1
1	2	6	0.00000E+00	0.00000E+00	1
1	2	7	2.08437E+01	2.08437E+01	1
1	2	8	0.00000E+00	0.00000E+00	1
1	4	1	2.88152E+02	2.88152E+02	1
1	4	2	0.00000E+00	0.00000E+00	1
1	4	3	0.00000E+00	0.00000E+00	1
1	4	4	3.90737E+02	3.90793E+02	1
1	4	5	0.00000E+00	0.00000E+00	1
1	4	6	0.00000E+00	0.00000E+00	1
1	4	7	2.08437E+01	2.08437E+01	1
1	4	8	0.00000E+00	0.00000E+00	1

Figure 5.14: An extract from the DAT file of the Day Care Facility pasted in the database

EvacSimulationID	EvacSimStartTime	EvacSimEndTime	TotalNumOfSimPeople	NumOfMale	NumOfFemale	NumOfPeopleOut
1	0	331.41	154	81	73	141
2	0	331.41	154	81	73	141
3	0	331.41	154	81	73	141
4	0	331.41	154	81	73	141
5	0	331.41	154	81	73	141
6	0	331.41	154	81	73	141
7	0	331.41	154	81	73	141

SimOccupantID	Gender	LevelID	Age	Weight	ResponseTime	DistanceTravelled
1	Male	1	25	80	60	6.56
2	Male	1	25	80	60	10.4
3	Male	1	73	48.28	65.19	4.24
4	Male	1	74	79.83	65.33	6.19
5	Female	1	75	75.36	72.1	2.82
6	Male	2	25	80	60	21.27
7	Male	1	77	85.37	66.09	11.07
8	Female	1	71	81.78	76.16	1.71
9	Female	1	81	40.51	72.9	5.14
10	Male	2	25	80	60	24.67
11	Male	1	72	58.57	70.25	8.86
12	Female	1	90	42.28	75.28	7.15
13	Female	1	79	52.42	71.52	11.16
14	Female	1	81	50.95	70.16	12.02
15	Female	1	75	60.57	82.13	3.71

Figure 5.15: An extract from the SIM file of the Day Care Facility pasted in the database

9. *Using the created web services, service provider adds the key results data from the fire and evacuation analysis database to the BIMserver as extended data:* As covered in Chapter 4, the FSE plugins for BIMserver contain services that were created to provide this functionality.

View/Query analysis data

Several queries have been created in the fire/analysis database that can be used for providing essential information about the simulated scenarios to the client. For instance, the following queries:

Query 1: Overall evacuation simulations summary for each scenario.

Query 2: Exits usage average for each scenario.

Query 3: Average RSET value for each scenario.

Query 4: ASET value for each scenario.

10. *From the web module, client run queries on the conducted fire and evacuation analysis data*: The web module presents a list of available queries which are from the fire and evacuation analysis database to the client that can be selected and executed. This offers a flexible approach to accessing information about the analysis outcome. Based on the analysis data, the service provider can record in the database an expert opinion of the overall outcome of the analysis as well as for each scenario. This information is then conveyed to the client using this query approach. See Figure 5.16 which shows the result of the selected query:

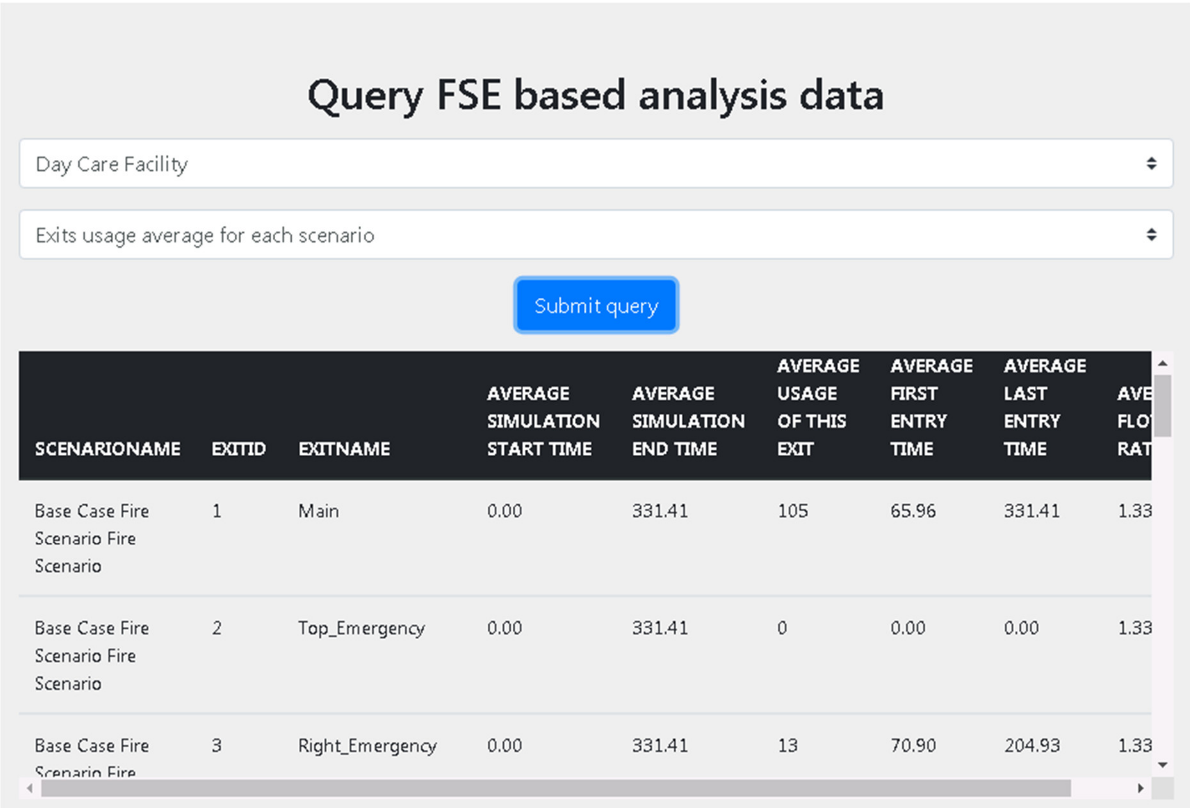

Figure 5.16: Day Care Facility – Result of the selected query

Important note: As can be seen from the fire and evacuation analysis outcome, Scenario 4 provided the desired solution. Therefore, the recommended design change, as communicated to the client, was adopted as shown in Figure 5.17.

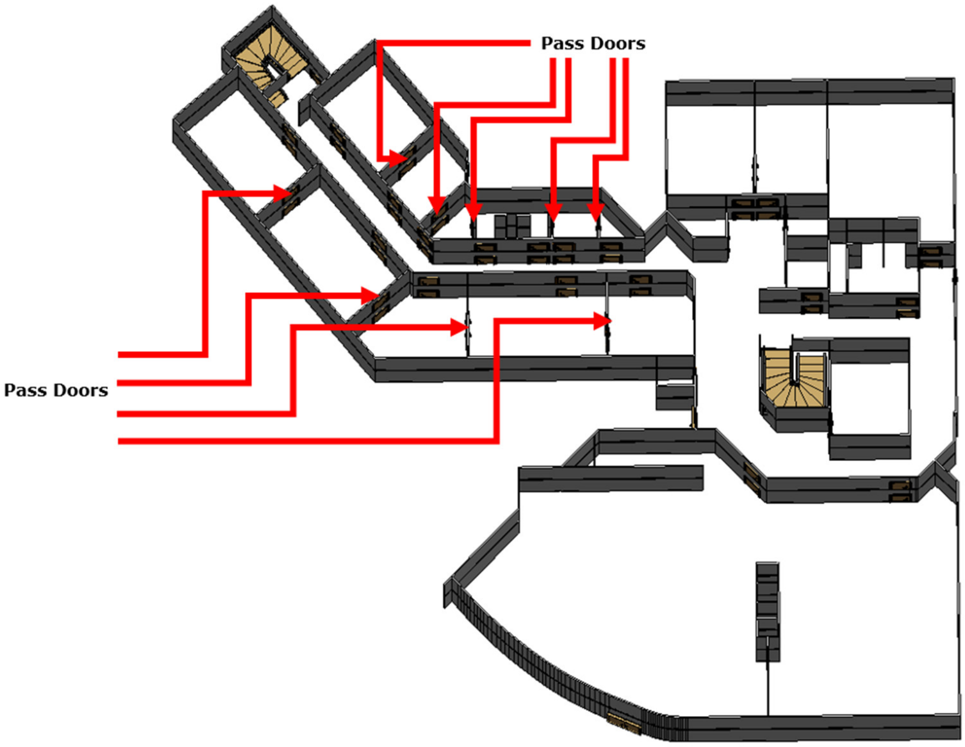

Figure 5.17: Day Care Facility – BIM model in Revit with pass doors added

5.3.2 Rhode Island Station Nightclub case study

The details of each step were described for the Day Care Facility case study and considering a similar approach is used for the Station Nightclub, only a brief description with some Figures is included here.

Make BIM data available

1. *Client exports the BIM model of the case study in IFC format from the BIM design tool it was created in:* The 3D model of the Station Nightclub was created in Revit 2018 and shown in Figure 5.2. The model export approach for the Day Care Facility was also used for this case study.

As was the case for the Day Care Facility, IFC Model viewer tool BIM Vision was used for a quick visualisation of the exported IFC file of the Station Nightclub as shown in Figure 5.18.

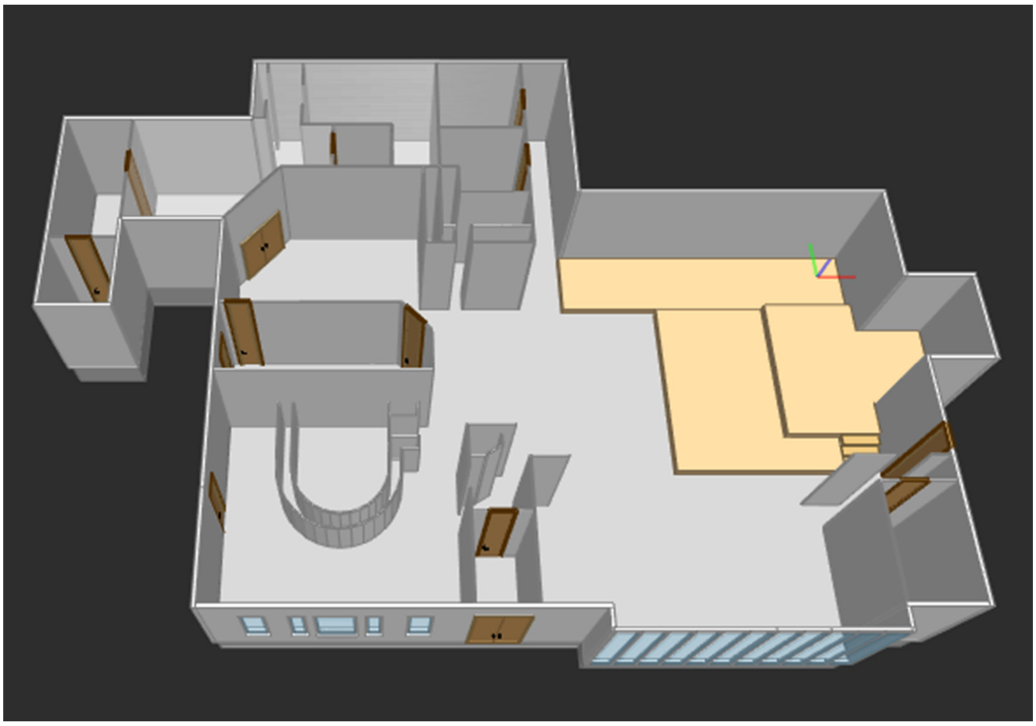

Figure 5.18: Station Nightclub IFC file opened in BIM Vision IFC Model viewer

2. *Client creates a project in BIMserver for the same case study and checks-in the IFC file:* In BIMserver, exported IFC file for the Station Nightclub from Revit was imported for the newly created project using the check-in option. See Figure 5.19.

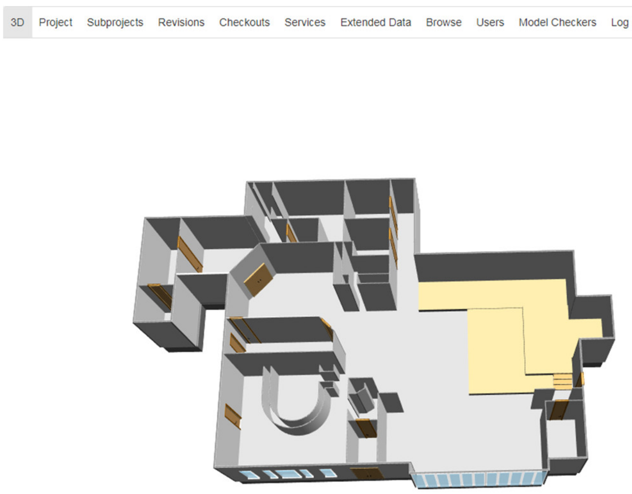

Figure 5.19: Station Nightclub project in BIMserver

3. *Client attaches the essential services and access account to the project:* A description of this process was provided for the Day Care Centre and therefore it is not repeated here.

4. *From the web module client submits FSE based analysis (ASET, RSET, both or coupled) request to the service provider:* A description of this process was provided for the Day Care Centre and therefore it is not repeated here. For the screenshot of the submitted request, see Figure 5.20.

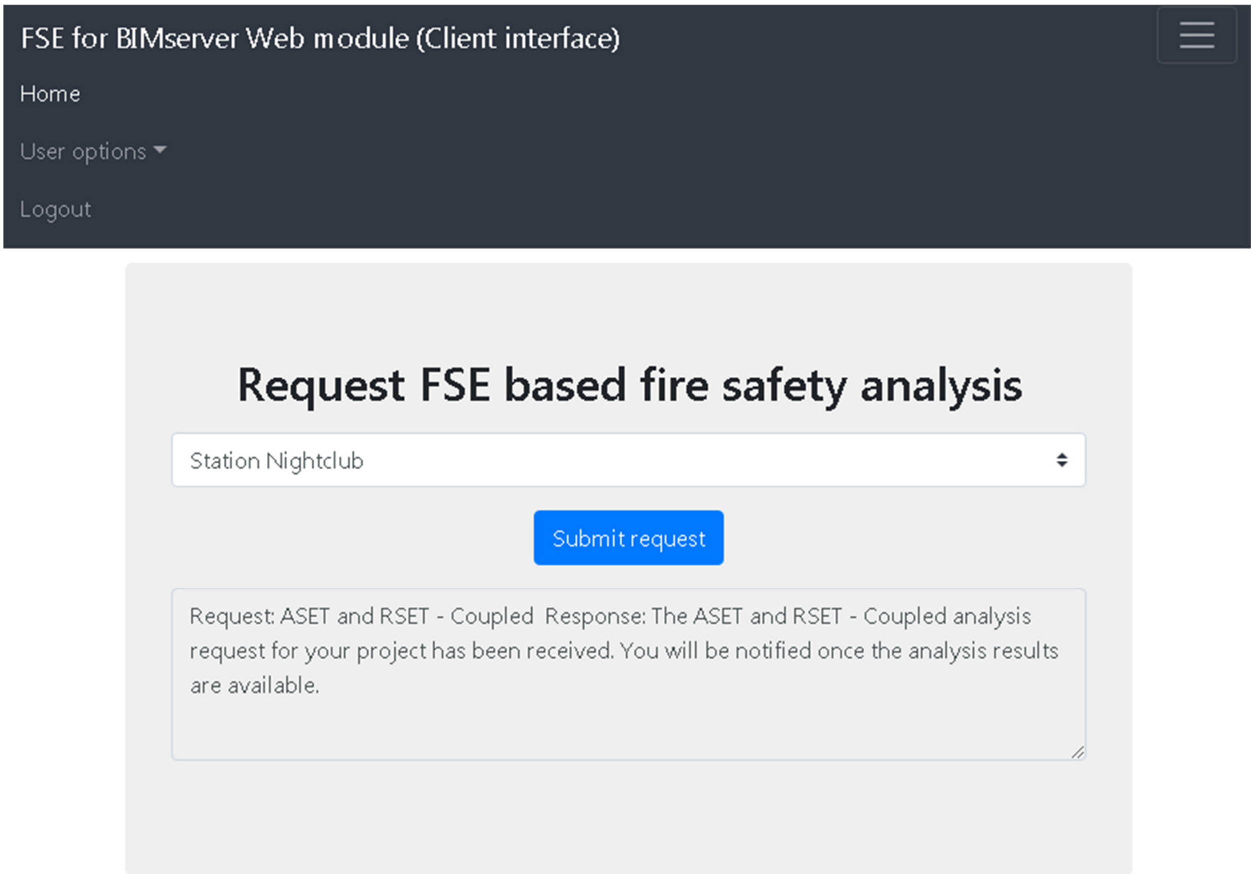

Figure 5.20: Submit a request for fire and evacuation analysis

Acquire BIM data

5. *From the web module, service provider downloads the IFC file which can then be imported in fire and evacuation modelling tool:* The process here is similar to what was used for the Day Care Facility and therefore the description is not repeated. For a screenshot of the file download feature, see Figure 5.21.

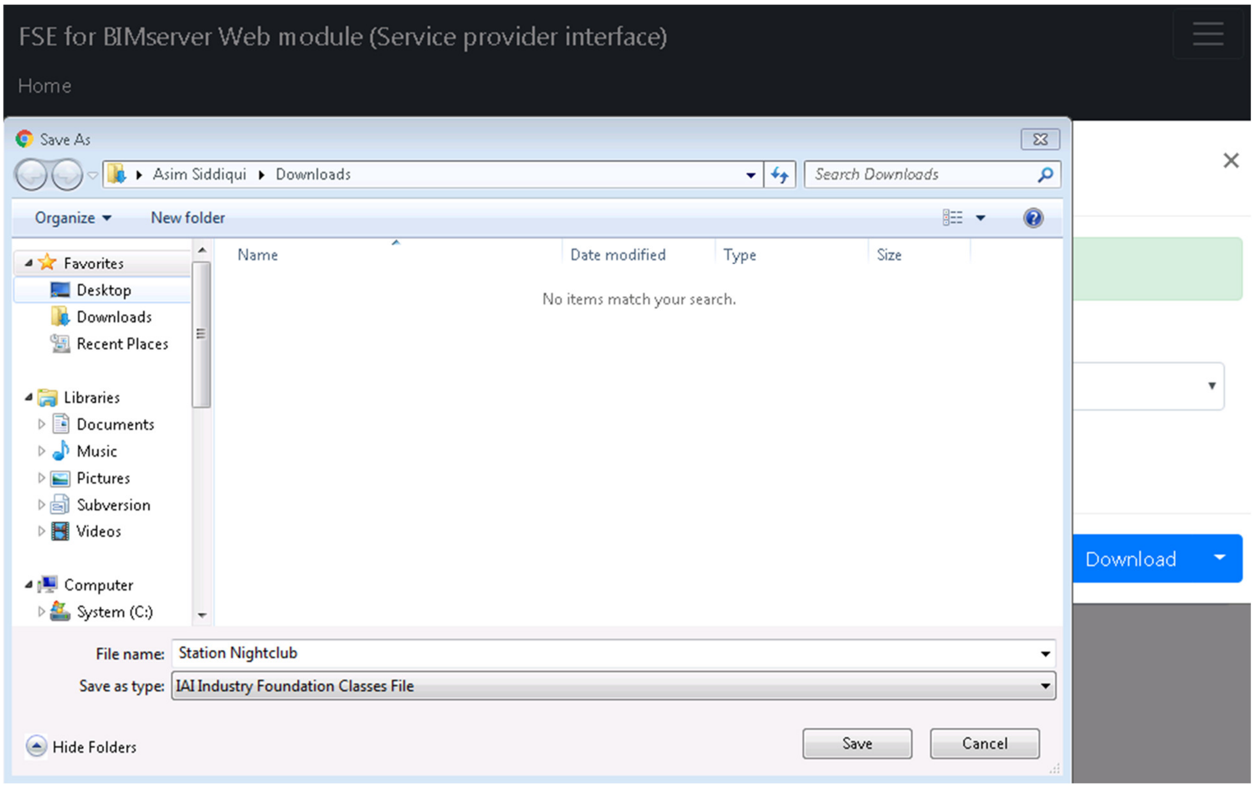

Figure 5.21: Download Station Nightclub IFC file

6. *Import IFC file in fire and evacuation modelling tool:*

The IFC file of the Station Nightclub was successfully imported in SMARTFIRE using the default options and is shown in Figure 5.22.

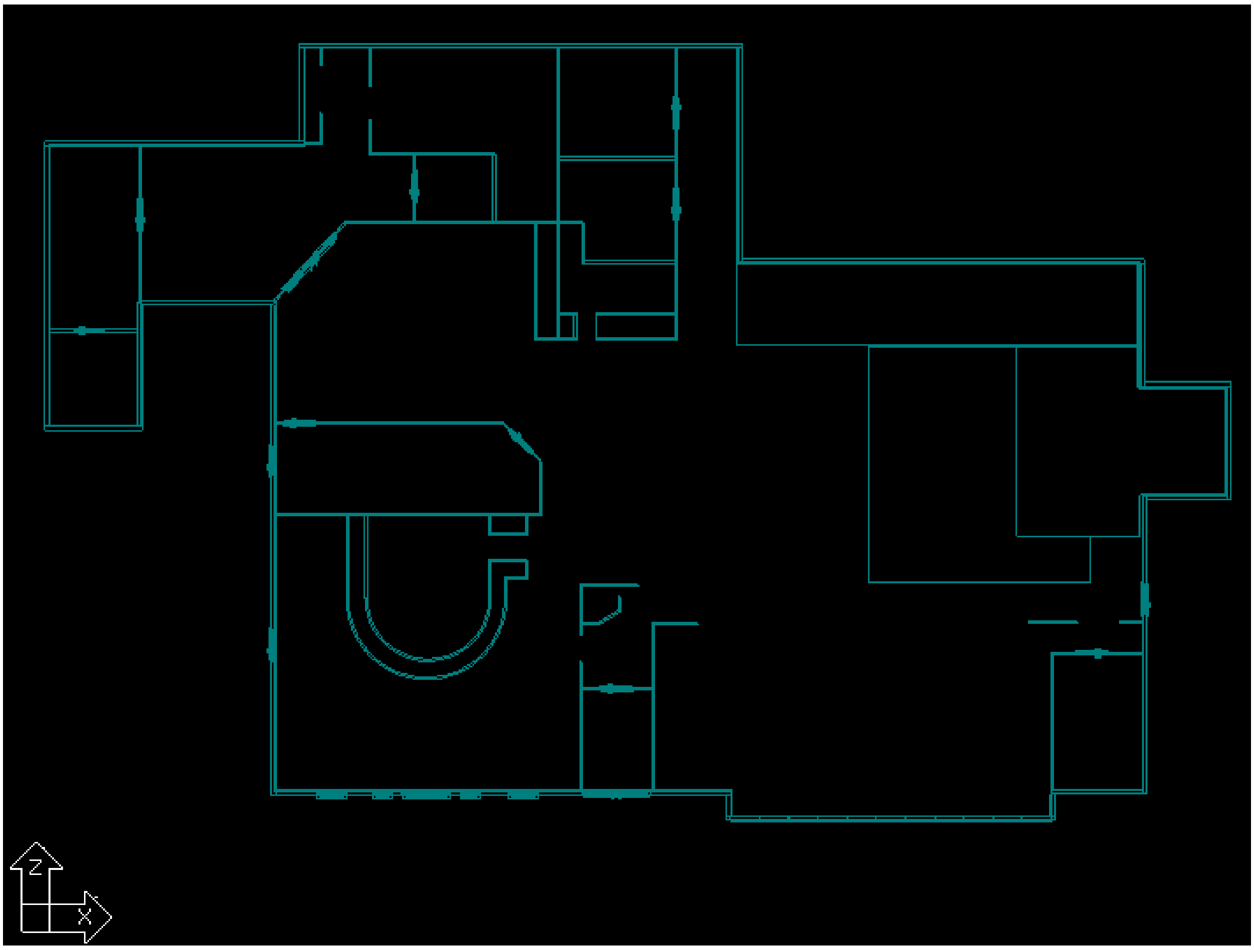

Figure 5.22: Station Nightclub IFC file imported in SMARTFIRE

Also, the IFC file of the Station Nightclub was successfully imported in buildingEXODUS using the default options and is shown in Figure 5.23.

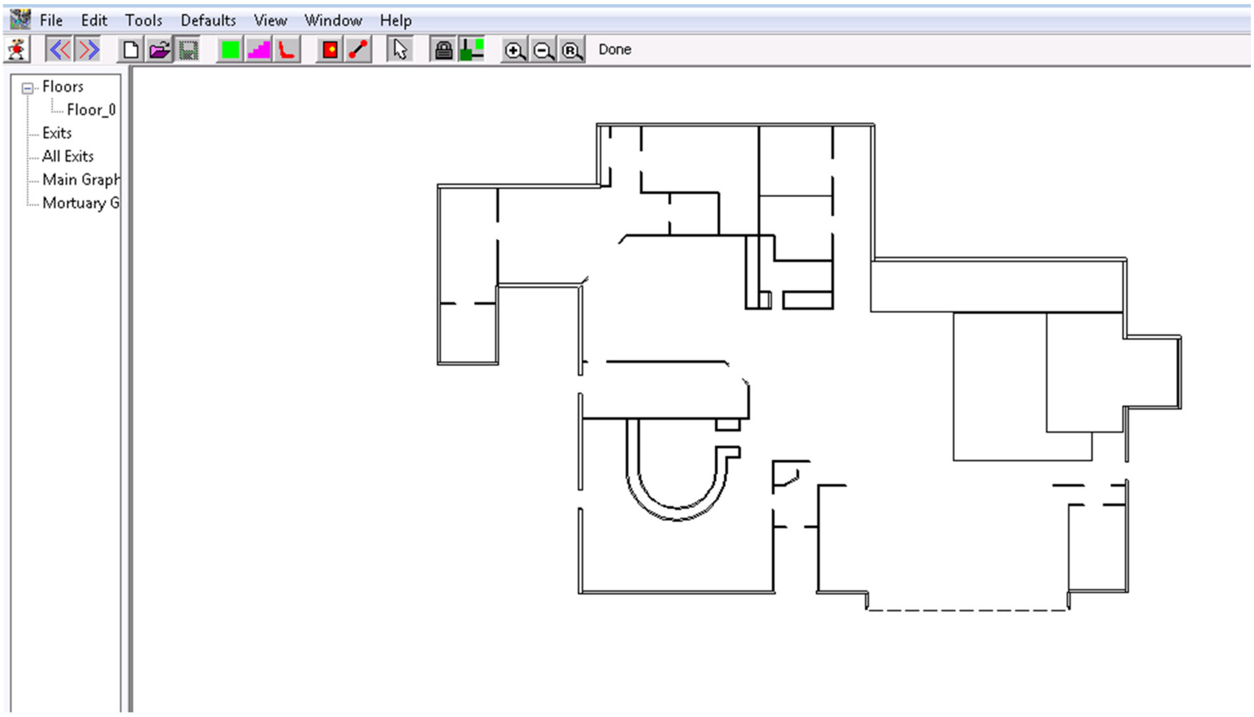

Figure 5.23: Station Nightclub IFC file imported in buildingEXODUS

Conduct fire and evacuation analysis

7. *Setup and run the simulations for the identified scenarios:*

As this is for forensic analysis, the idea was to simulate the incident so actually, there is one scenario but three ways it was analysed and modelled in SMARTFIRE for fire analysis and buildingEXODUS for the evacuation analysis. Nevertheless, in-line with Galea *et al.* (2008), these three ways are treated as scenarios and were simulated as mentioned below:

Scenario 1: Evacuation simulation without coupled fire atmosphere i.e. the impact of fire hazards on the population was not directly considered as the evacuation and fire simulations were not coupled.

Scenario 2: Evacuation simulation coupled to fire simulation i.e. the impact of fire hazards on the population was directly considered as the evacuation and fire simulations were coupled.

Scenario 3: Same as Scenario 2 but with a 15 second delay in the time to flashover.

All the required data to setup and run simulations was acquired at the previous step. At this step, selected fire and evacuation modelling tools SMARTFIRE and buildingEXODUS were prepared to run the simulation for the identified scenarios. For evacuation analysis in buildingEXODUS, 20 simulations were run for each scenario.

Note: For scenarios in buildingEXODUS, response times of 25-30 sec, 30-35 sec and 35-41 sec were assigned to occupants at the dance floor, the bar area and the office and other spaces respectively.

Scenario 1: First, based on the analysis in SMARTFIRE, the simulated fire data was generated. As the impact of fire on the population was not needed for this scenario i.e. not coupled analysis, buildingEXODUS simulations were run without loading the fire hazard data. The main outcome of the simulations is that the average last person out time was 124.4 seconds.

Scenario 2: Same as for Scenario 1 but using the coupled fire and evacuation approach. First based on the analysis in SMARTFIRE, the simulated fire data which was generated for Scenario 1 was made available to use in buildingEXODUS for this scenario to cater for the impact of fire hazards on the population. In buildingEXODUS, the fire data for Scenario 2 was loaded and 20 simulations were run. The main outcome of the simulations is the high number of fatalities (average 180) for Scenario 2.

Scenario 3: As in Scenario 2 using coupled fire and evacuation analysis, but with 15 second delay in the predicted fire timeline. Based on the analysis in SMARTFIRE, the simulated fire data generated in Scenario 1 was made available to use in buildingEXODUS to cater for the impact on fire hazards on the population. In buildingEXODUS, this fire data was loaded, and 20 simulations were run. The main outcome of the simulations is that the number of fatalities was significantly lower (average 84) than in Scenario 2 and relatively close to the number in actual incident i.e. 100.

Share analysis simulation results with BIM

8. *Export the fire and evacuation modelling generated simulation data for all the scenarios to the fire and evacuation analysis database:*

SMARTFIRE generated fire data file is in DAT format. As an example, some selected columns and rows of the DAT file which was generated for Scenario 1 is shown in Figure 5.24.

```
 7  31
temp
hcn
rad
co2
co
o2
smoke
    1       0.000  2.88165e+002  2.88147e+002  0.00000e+000  0.00000e+000  3.90890e+002  3.90870e+002
    2       0.000  2.88152e+002  2.88152e+002  0.00000e+000  0.00000e+000  3.90870e+002  3.90874e+002
    3       0.000  2.88134e+002  2.88165e+002  0.00000e+000  0.00000e+000  3.90848e+002  3.90887e+002
    4       0.000  2.88149e+002  2.88150e+002  0.00000e+000  0.00000e+000  3.90867e+002  3.90873e+002
    5       0.000  2.88151e+002  2.88149e+002  0.00000e+000  0.00000e+000  3.90873e+002  3.90870e+002
    6       0.000  2.88150e+002  2.88150e+002  0.00000e+000  0.00000e+000  3.90873e+002  3.90874e+002
    7       0.000  2.88152e+002  2.88144e+002  0.00000e+000  0.00000e+000  3.90864e+002  3.90867e+002
    8       0.000  2.88148e+002  2.88149e+002  0.00000e+000  0.00000e+000  3.90873e+002  3.90872e+002
    9       0.000  2.88151e+002  2.88151e+002  0.00000e+000  0.00000e+000  3.90872e+002  3.90871e+002
   10       0.000  2.88148e+002  2.88152e+002  0.00000e+000  0.00000e+000  3.90868e+002  3.90875e+002
   11       0.000  2.88150e+002  2.88150e+002  0.00000e+000  0.00000e+000  3.90872e+002  3.90872e+002
   12       0.000  2.88148e+002  2.88152e+002  0.00000e+000  0.00000e+000  3.90871e+002  3.90875e+002
   13       0.000  2.88159e+002  2.88148e+002  0.00000e+000  0.00000e+000  3.90871e+002  3.90873e+002
   14       0.000  2.88150e+002  2.88152e+002  0.00000e+000  0.00000e+000  3.90873e+002  3.90873e+002
   15       0.000  2.88151e+002  2.88150e+002  0.00000e+000  0.00000e+000  3.90870e+002  3.90872e+002
   16       0.000  2.88155e+002  2.88149e+002  0.00000e+000  0.00000e+000  3.90873e+002  3.90871e+002
```

Figure 5.24: An extract of the SMARTFIRE generated fire data DAT file

In case of buildingEXODUS, simulation data is in SIM extension files. As an example, extracts of data from one of the SIM files for Scenario 1 is shown in Figure 5.25.

```
Number of People out 460, first out (secs) 29.56  last 122.58

Final Simulation time 122.58

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++


Exit results table:-

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

  Pos|Gender      |Start Node  |  Age|  Weight|Mobility|Response|End Node     |      CWT|Distance|
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    1|Female      |FreeSpace_0 |   20|   50.00|    1.00|   25.71|Platform_Exit|     1.46|    0.57|
    2|Male        |FreeSpace_0 |   20|   59.00|    1.00|   24.06|Platform_Exit|     1.84|    2.62|
    3|Male        |FreeSpace_0 |   35|   69.00|    1.00|   25.29|Platform_Exit|     2.40|    2.28|
    4|Female      |FreeSpace_0 |   56|   58.00|    1.00|   24.31|Platform_Exit|     3.06|    2.67|
    5|Male        |FreeSpace_0 |   32|   71.00|    1.00|   27.19|Platform_Exit|     2.28|    2.28|
    6|Male        |FreeSpace_0 |   25|   68.00|    1.00|   25.66|Platform_Exit|     2.06|    3.46|
    7|Male        |FreeSpace_0 |   20|   58.00|    1.00|   25.09|Main_Exit    |    0.00|    6.86|
    8|Male        |FreeSpace_0 |   25|   80.00|    1.00|   25.39|Platform_Exit|     3.59|    4.80|
    9|Male        |FreeSpace_0 |   34|   65.00|    1.00|   26.60|Platform_Exit|     2.01|    3.72|
   10|Male        |FreeSpace_0 |   45|   67.00|    1.00|   25.38|Main_Exit    |    0.00|    6.85|
   11|Female      |FreeSpace_0 |   34|   58.00|    1.00|   26.89|Main_Exit    |    1.11|    6.55|
   12|Female      |FreeSpace_0 |   51|   52.00|    1.00|   27.00|Platform_Exit|     4.42|    4.01|
   13|Male        |FreeSpace_0 |   22|   73.00|    1.00|   28.42|Platform_Exit|     2.37|    3.28|
   14|Female      |FreeSpace_0 |   48|   57.00|    1.00|   24.01|Main_Exit    |    2.93|   10.90|
   15|Female      |FreeSpace_0 |   57|   53.00|    1.00|   24.90|Main_Exit    |    0.56|    8.68|
```

Figure 5.25: Data extracts of the buildingEXODUS generated SIM file

The data transfer process from the DAT and SIM files to the database is similar to what was described for the Day Care Facility and therefore it is not repeated here.

Figure 5.26 and Figure 5.27 show extracts of data pasted in the database from the DAT and SIM files for the Station Nightclub.

HazardTypeID	HazardTypeName	HazardTypeDescription
1	Temp	Temperature
2	hcn	Hydrogen cyanide
3	rad	Radiation
4	co2	Carbon dioxide
5	co	Carbon monoxide
6	o2	Oxygen
7	smoke	Smoke

FireEvacZoneID	TimeInterval	HazardType	UpperValue	LowerValue	FireSimID
1	0	1	2.88165E+02	2.88147E+02	
1	0	2	0.00000E+00	0.00000E+00	
1	0	3	3.90890E+02	3.90870E+02	
1	0	4	0.00000E+00	0.00000E+00	
1	0	5	0.00000E+00	0.00000E+00	
1	0	6	0.00000E+00	0.00000E+00	
1	0	7	0.00000E+00	0.00000E+00	
1	6.3	1	2.89085E+02	2.88149E+02	
1	6.3	2	7.74848E-01	5.39608E-12	
1	6.3	3	3.96421E+02	3.93354E+02	
1	6.3	4	1.03867E-02	7.80554E-14	
1	6.3	5	1.63983E+01	1.23232E-10	
1	6.3	6	2.08293E+01	2.08440E+01	
1	6.3	7	2.34139E-02	2.05168E-13	
1	12.6	1	2.93799E+02	2.88165E+02	
1	12.6	2	4.28381E+00	3.45770E-12	
1	12.6	3	4.37680E+02	4.13386E+02	
1	12.6	4	5.72513E-02	4.99731E-14	
1	12.6	5	9.03869E+01	7.88961E-11	
1	12.6	6	2.07645E+01	2.08440E+01	
1	12.6	7	1.21944E-01	1.31591E-13	

Figure 5.26: Data extract from the DAT file of the Station Nightclub pasted in the database

EvacSimulationID	EvacSimStartTime	EvacSimEndTime	TotalNumOfSimPeople	NumOfMale	NumOfFemale	NumOfPeopleOut
1	0	122.58	460	259	201	460
2	0	125.27	460	259	201	460
3	0	126.62	460	259	201	460
4	0	124.75	460	259	201	460
5	0	124.86	460	259	201	460
6	0	126.14	460	259	201	460
7	0	124.42	460	259	201	460

SimOccupantID	Gender	LevelID	Age	Weight	ResponseTime	DistanceTravelled
1	Female	1	20	50	25.71	0.57
2	Male	1	20	59	24.06	2.62
3	Male	1	35	69	25.29	2.28
4	Female	1	56	58	24.31	2.67
5	Male	1	32	71	27.19	2.28
6	Male	1	25	68	25.66	3.46
7	Male	1	20	58	25.09	6.86
8	Male	1	25	80	25.39	4.8
9	Male	1	34	65	26.6	3.72
10	Male	1	45	67	25.38	6.85
11	Female	1	34	58	26.89	6.55
12	Female	1	51	52	27	4.01
13	Male	1	22	73	28.42	3.28
14	Female	1	48	57	24.01	10.9
15	Female	1	57	53	24.9	8.68

Figure 5.27: Data extract from the SIM file of the Station Nightclub pasted in the database

Important note: An additional test was also conducted using a combination of database query and a web service to calculate the ASET value for a scenario. The idea was to run this web service after the analysis data has been entered in the database to calculate the ASET value based on set criteria. For this test, the ASET value was calculated by finding an average time value for all identified zones when the specified tenability criteria were reached. As the ASET value can be calculated in more than one way depending on the specified criteria (Galea *et al.*, 2008), this process can be somewhat automated with multiple calculation options presented to the expert user. This test successfully calculated the ASET value and offers an opportunity to explore this idea further in the future.

9. *Using the created web services, service provider adds the key results data from the fire and evacuation analysis database to the BIMserver as extended data:* As covered in Chapter 4, the FSE plugins for BIMserver contain services that were created to provide this functionality.

View/Query analysis data

Some queries that can be suitable for various case studies were mentioned previously for the Day Care Centre and therefore are not repeated here.

10. *From the web module, client run queries on the conducted fire and evacuation analysis data*: For the Station Nightclub, several queries are presented to the client in a drop-down box which can be selected and executed. See Figure 5.28 which shows the result of the selected query.

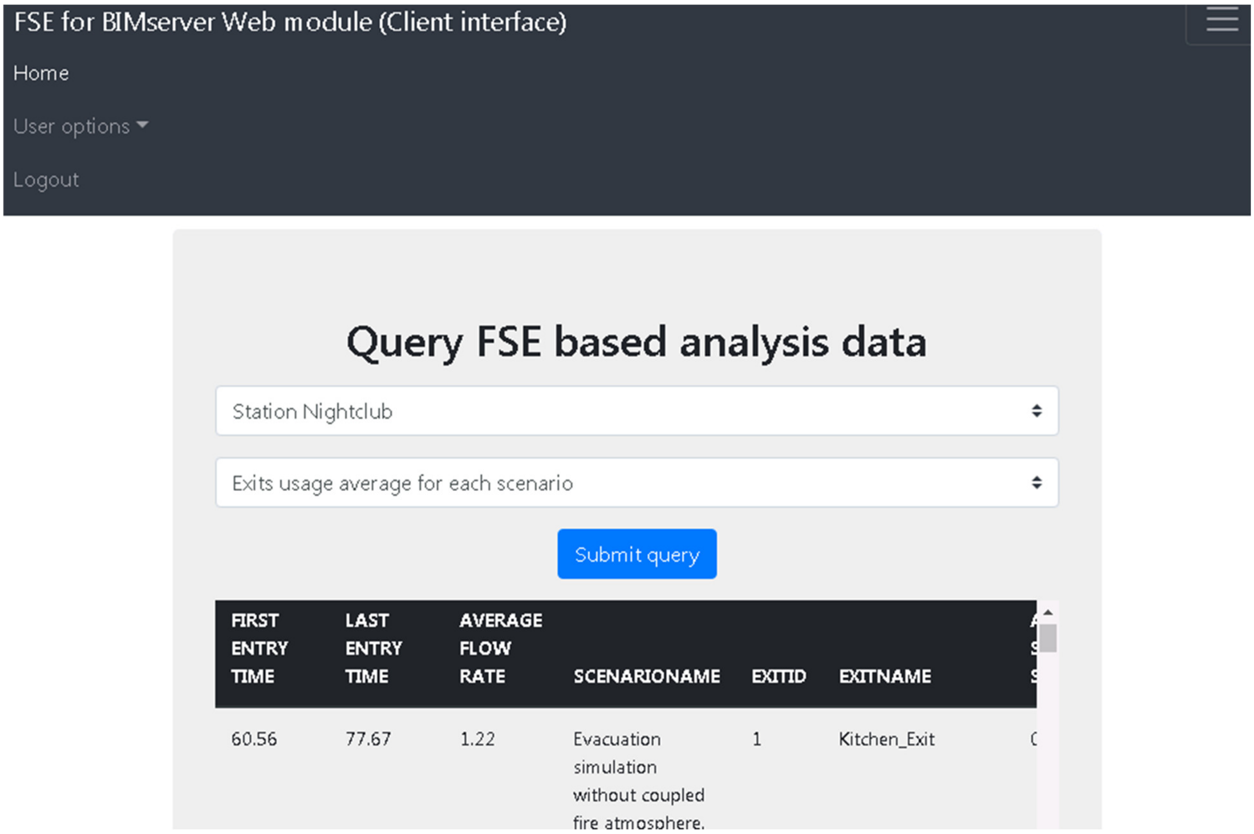

Figure 5.28: Station Nightclub– Result of the selected query

5.3.3 Summary of testing outcome

The data sharing between BIM and FSE using fire and evacuation modelling tools, for the design phase and post incident forensic analysis, using the Day Care Facility and the Station Nightclub was successfully demonstrated in this chapter. To achieve this data sharing, the key role was played by the fire and evacuation analysis database, the FSE for BIMserver services bundle, and the FSE for BIMserver web module. As part of the development work in support for the FSE with BIM strategy presented in Chapter 4, the main objective of this testing was to practically demonstrate using suitable case studies that this type of communication is possible. Although some limitations were reported in Chapter 4, the following two-way communication was successfully demonstrated:

- BIM data in standard IFC file format was transferred from BIM design tool to fire and evacuation modelling tools facilitated by Revit, BIMserver, FSE for BIMserver services bundle, FSE for BIMserver web module, and IFC import utilities developed by FSEG.
- Fire and evacuation simulation results were transferred to the fire and evacuation analysis database even though currently it is not an automated process.
- The fire and evacuation simulation results were then shared with BIM, enabled by the FSE for BIMserver services bundle and the FSE for BIMserver web module.

Some benefits of the data sharing between BIM and FSE demonstrated through the prototype system are listed below:

- Client and service provider approach which offers ease in communication through a web frontend.
- Audit trail of key steps of communication is captured which can be beneficial for future reference.
- Essential FSE based analysis data is captured, stored and shared in a structured way.
- Several Level 3 BIM concepts (e.g. server hosted single shared project model, Open BIM concept of buildingSMART using standards such as IFC, and web services approach) are used by this system.
- Potential for future automation (e.g. FSE related clash detection and consistency checking).

For the production system, this prototype will be improved, adjusted, and developed further and go through user testing. The details of suggested improvements and further developments are covered in the Conclusions and Future work Chapter 6. However, for proof of concept purpose, the prototype system has successfully demonstrated two-way data sharing between BIM and FSE based analysis using fire and evacuation modelling tools.

6 CONCLUSIONS AND FUTURE WORK

In this chapter, the main conclusions of this research are presented. The research question and objectives set out in Chapter 1 are then reviewed in light of these main conclusions. Finally, a description of future development to enhance the presented work is provided.

6.1 Conclusions

This study has identified key challenges and limitations facing the use and involvement of FSE in the context of BIM. Currently, even though reasonable support in BIM exists for the input data required for FSE, there is no explicit provision for the fire and evacuation modelling generated essential output data even though some BIM packages such as Revit do provide options to add custom data sets to any element. Furthermore, fire and evacuation modelling have limited support for BIM. In response to these issues, a strategy for using FSE with BIM was proposed which provided a road map for effective use of FSE within the context of BIM by addressing the current limitations as well as highlighting the inherited issue of lack of sub-model for FSE and limited support for BIM in fire and evacuation modelling tools, whilst supporting the future direction of BIM development. Development work in support of this strategy was carried out, that included a prototype database for capturing FSE based analysis fire and evacuation modelling generated data, and also a prototype system to demonstrate sharing of data between BIM and FSE based analysis using fire and evacuation modelling tools. First, a summary of key outcomes, on a chapter by chapter basis is presented which is then followed by a description of how the research question was answered.

Key outcomes for each chapter

Chapter 2: In this chapter, an extensive literature review was conducted covering the data sharing aspects mainly for BIM and FSE but additionally in Smart Buildings as well. The literature review indicated various gaps in knowledge and based on that the following key conclusions were made:

- There is currently a lack of coherent strategy to utilise the full benefits of FSE with BIM combination. The following points should be noted:

  - There is a reasonable level of support in the BIM IFC Model specification for essential FSE data input but the sharing of key FSE based analysis output data using the fire and evacuation tools is currently missing. Furthermore, currently, BIM building design tools have no data export facilitates which are intended for consumption by the FSE based analysis fire and evacuation modelling tools.
  - As far as the fire and evacuation modelling tools are concerned, currently, the support for BIM is limited and restricted to geometry extraction. For fire and evacuation modelling tools there is no single independent organisation controlling standards and that is why there is no one standard data exchange format for sharing simulations generated data between various tools.
- There is support for Smart Building systems in BIM IFC Model specification, but its adoption is at an early stage. Without addressing the FSE support at the IFC specification level, it will not be possible to fully realise the potential benefits that an application utilising BIM with FSE combination in a Smart Building environment can offer. In other words, the initial focus should be on resolving the deficiencies in FSE with BIM data sharing support.

Based on the above, this chapter has either fully or partially addressed Question 1a i.e. What are the essential data input and output requirements for FSE based analysis using fire and evacuation modelling tools?, Question 1b i.e. What current level of support is there in BIM for FSE based analysis using fire and evacuation modelling tools?, Question 1c i.e. What current level of support is there in fire and evacuation modelling tools for BIM?, and Question 1f i.e. What level of support do Smart Building systems have in BIM?

<u>Chapter 3</u>: In this chapter, in response to the identified gaps in knowledge, a strategy for FSE with BIM data sharing was proposed. This strategy proposed a step by step process targeting the limitations in BIM IFC Model specification, implementation of the specification in BIM design tools, and enhanced support for BIM in fire and evacuation modelling tools.

Based on the above, this chapter has addressed Question 1d i.e. Can a strategy be defined to address the limitations in data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

<u>Chapter 4</u>: In this chapter, the development work in support of the strategy for BIM with FSE data sharing and a proof of concept system to demonstrate that was presented. To support the strategy, the following development work was undertaken:

- The proposed key FSE based analysis data using fire and evacuation modelling tools for FSE information exchange for BIM was captured in a database schema and its implementation in a representative DBMS was presented. This work is expected to assist in the development of an MVD for FSE as part of the collaboration project proposal to buildingSMART.
- A proof of concept system to demonstrate the data sharing between BIM and FSE, including web services bundle and Web frontend for the BIMserver, was presented. Although there are some limitations, the data sharing between BIM and FSE was successfully established and ready to be tested with suitable case studies.
- The findings and recommendations based on this study for enhancing BIM support in fire and evacuation modelling tools SMARTFIRE and buildingEXODUS were provided. These recommendations will be used by the FSEG for future enhancements of SMARTFIRE and buildingEXODUS in support of BIM data.
- A conceptual design of BIM-enabled Smart Signage Management System was presented as an example application of BIM with FSE data sharing in a Smart Building environment during the operational phase of the building lifecycle. It was not possible to implement and test this proposed system as part of this study due to the required practical resources and time constraints.

Based on the above, this chapter has either fully or partially addressed Question 1e: How to demonstrate data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?, and Question 1g: Can a suitable conceptual design be outlined that can utilise BIM and FSE based analysis using fire and evacuation modelling tools in a Smart Building environment?

Chapter 5: Finally, in this chapter, using two suitable case studies namely, Day Care Facility and the Station Nightclub respectively, two-way data sharing between BIM and FSE based analysis using fire and evacuation modelling tools was successfully demonstrated. These case studies catered for data sharing during design as well as for post incident forensic analysis.

Based on the above, this chapter has fully addressed Question 1e: How to demonstrate data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

How the research question was addressed

Chapter 1 sets out the scope of this study and put forward a research question. This was followed by an indication of how these questions will be addressed by the aid of specific objectives using a specified approach. The research question was: **How can effective data sharing be achieved between BIM and FSE based analysis using fire and evacuation modelling tools?**

This question consisted of five main and two additional sub-questions and following is a description of how they were addressed:

Question 1a: What are the essential data input and output requirements for FSE based analysis using fire and evacuation modelling tools?

The Question 1a was partially tackled in Chapter 2 as indicated already in this chapter in the **Key outcomes for each chapter** section. Briefly, in Chapter 2, the literature review shed light on the following: fire modelling, evacuation modelling, data sharing between fire and evacuation modelling tools, the input of fire data in evacuation modelling tools, and the input of evacuation data in fire modelling tools. Based on the literature review, an understanding of the level of data requirements for fire and evacuation modelling tools was acquired. However, as Question 1a, 1b and 1c were closely linked, a more detailed analysis was needed to identify specific data requirements for FSE with BIM. In Chapter 3, the strategy to deal with the limitations of FSE with BIM data sharing, as indicated by the literature review in Chapter 2, was presented. The key task of the first step of this strategy was the identification of input and output data for fire and evacuation modelling tools for use with BIM. A description of this key task was included in Chapter 3 which was then addressed in detail in Chapter 4 where an essential data input and output requirements of fire and evacuation modelling tools were identified and presented in a tabular format.

Question 1b: What current level of support is there in BIM for FSE based analysis using fire and evacuation modelling tools?

The Question 1b was initially tackled in Chapter 2 as indicated already in this chapter in the **Key outcomes for each chapter** section. Briefly, the literature review indicated a reasonable level of support in BIM IFC Model for FSE required input data. However, the review also indicated no explicit support in BIM IFC Model for the FSE based analysis output data.

Question 1c: What current level of support is there in fire and evacuation modelling tools for BIM?

The Question 1c and Question 1b are closely linked and therefore they were addressed together in the dissertation. In Chapter 2, a review of fire and evacuation modelling tools covering the data input and output support for BIM provided an indication of limited geometry extraction support in a small number of tools.

Question 1d: Can a strategy be defined to address the limitations in data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

The Question 1d was tackled in Chapter 3 where a strategy to address the limitations of FSE with BIM data sharing was presented. This proposed three step strategy provided a road map to address the current limitations in data sharing between BIM and FSE. An important step of the strategy is the development of an MVD for FSE and for that, a collaboration project proposal to buildingSMART is in progress. The development work in support of this strategy was then covered in Chapter 4 that included a prototype database for capturing FSE based analysis data and recommendations for enhancements in fire and evacuation modelling tools SMARTFIRE and buildingEXODUS respectively, which were used as representative examples.

Question 1e: How to demonstrate data sharing between BIM and FSE based analysis using fire and evacuation modelling tools?

The Question 1e was addressed in Chapter 4 and Chapter 5. In Chapter 4, a description was provided of a prototype system that has been developed to demonstrate the data sharing between BIM and FSE based analysis using fire and evacuation modelling tools. As part of this prototype system, web services and web frontend were developed which facilitated the data sharing. This prototype system was then tested successfully using a couple of selected case studies and a description of that was included in Chapter 5.

By addressing above mentioned five sub-questions i.e. Questions 1a, 1b, 1c, 1d and 1e, it can be asserted that effective data sharing between BIM and FSE is possible and can be addressed by the proposed solution. Therefore, the main part of Question 1 has been addressed.

For the research question, two additional sub-questions were also set to address the potential implication on the applications to Smart Buildings. A description of how these two additional sub-questions were addressed is given below:

Question 1f: What level of support do Smart Building systems have in BIM?

The Question 1f was tackled in Chapter 2 where the literature review indicated general support in BIM IFC Model for Smart Building system mainly within building control domain. However, its adoption in the industry is at an early stage.

Question 1g: Can a suitable conceptual design be outlined that can utilise BIM and FSE based analysis using fire and evacuation modelling tools in a Smart Building environment?

The Question 1g was addressed in Chapter 4 where a conceptual design of an application was presented which uses BIM with FSE in a Smart Building environment. This proposed BIM-enabled Smart Signage Management System can utilise a combination of BIM with FSE during the operational phase of the building lifecycle. Considering the lack of practical resources required for the implementation of this type of system and the time constraints, it was not possible to undertake an implementation work for this application as part of this study.

By addressing the two sub-questions i.e. Question 1f and 1g as mentioned above, it can be stated based on the conceptual design of the Smart Signage Management System that the FSE with BIM combination can be utilised in a Smart Building environment. However, to test this application, a prototype system should be developed. As only a conceptual design was required as part of this study, the implementation aspects should be addressed in another project that can take this work further.

Finally, based on the above, it can be concluded that both the main and additional parts of the research question have been answered.

Contribution to knowledge

The contribution to knowledge of this study has already covered in Chapter 1 but has been repeated here.

Impact on the BIM standard: This study has opened the door for the possibility of a collaboration project on the development of an MVD for FSE. If the project proposal is accepted by the BIM standards organisation buildingSMART then the development work will have a direct impact on the future version of IFC specification. The first part of the proposed MVD development work will be the identification of the information exchange for FSE. The following development work which was part of this study can assist in finalising the FSE information exchange requirements:

- The FSE based analysis preliminary database schema and its sample implementation for the proposed FSE information exchange within the BIM context. This database captures the key fire safety analysis data generated by fire and evacuation modelling tools.
- A prototype system using suitable test cases as examples to demonstrate data sharing between BIM and FSE by utilising the development work as part of the proposed strategy. This system provides proof of concept for the proposed strategy.

Recommendations for enhanced support for BIM in fire and evacuation modelling tools: The recommendations made as part of the proposed strategy for enhancing the capabilities of fire and evacuation modelling tools such as SMARTFIRE and buildingEXODUS will improve support for BIM.

Concluding remarks

There are clear benefits to BIM of having FSE as an integral component. These include: the possibility of iterative design checking without the costly problems caused by having only weakly coupled FSE; FSE can be used beyond the design phase for applications such as the BIM-enabled Smart Signage Management System; and BIM can support evolving fire safety requirements during the life cycle of a building. Moreover, if the key fire and evacuation generated simulation data become part of the future IFC specification then it will also offer an opportunity to add a fire safety analysis layer to the Architectural model. In other words, a fire safety analysis sub-model that can provide information such as ASET and RSET values and exit usage for various scenarios based on the fire and evacuation analysis data.

The strategy presented in this study provides an informed future direction for further development from the BIM with FSE perspective. However, there is a need for FSE practitioners to be more active and involved in the future development of BIM and the BIM community to support the proposed improvements.

Finally, as pointed out previously, to make FSE an integral part of BIM, a step by step process should be followed. Several hurdles must be crossed before the goal of fully integrated Level 3 BIM is realised particularly from the FSE perspective. However, this work has demonstrated that effective data sharing is possible between BIM and FSE. This is a step towards fully integrated Level 3 BIM from the FSE perspective.

6.2 Future work

The development work and ideas presented in this study can be extended in the following ways:

Enhancements in fire and evacuation modelling tools for BIM support

<u>IFC Import enhancements</u>: Based on the proposed improvements, the FSEG are either already working or will be on extending the capability of IFC import feature in buildingEXODUS. Similarly, for SMARTFIRE, the current IFC import feature which allows extraction of geometry is for internal use, but it will be included in the next release version. Some of the enhancements include the following:

- Automatic extraction of components such as staircases and lifts to speed up model generation.
- Extraction of *IfcSpace* elements and constructing a connectivity graph from the *IfcRelSpaceBoundary* relationships.
- Automatic extraction of compartment/room connectivity to allow for improved agent navigation.
- Extraction of location data of smoke management components and furniture elements.
- Extraction of material properties in SMARTFIRE.
- Extraction of data in FSE relevant property sets (e.g. *Pset_SpaceFireSafetyRequirements* and *Pset_SpaceOccupancyRequirements*) if available.
- Extraction of zone data (if specified) from an IFC file. See Chapter 4 for a description of why the extraction of this data from an IFC in SMARTFIRE can speed up the data input setup process.
- Currently, the IDs of objects (e.g. walls and doors) in IFC are not retained by the IFC import utilities in buildingEXODUS and SMARTFIRE. For future data sharing with BIM,

for accuracy and reference purpose, these IDs should be retained and additionally assigned to the key objects such as exit doors when analysis data is exported.

<u>The output of fire and evacuation generated data in a commonly used format</u>: Currently, the fire data generated by SMARTFIRE is exported in native DAT format while the evacuation generated data by buildingEXODUS is in native SIM format. It is recommended that this data should also be exported in a popular standard format such as JSON/XML, using the structure like the one proposed by the prototype database. See ifcJSON in Section 4.5.

Refinement and enhancements to the FSE based analysis preliminary database

The FSE based analysis database can be extended to include more details such as stairs usage, exit signs usability. This will be achieved by creating more tables in the database then conducting data input tests with relevant case studies.

Prototype system improvement work

A certain level of automation was introduced in the web-based prototype system, but a significant amount of improvements can be made. For instance, the following are suggested:

- The transfer of fire and evacuation simulation data from the fire and evacuation modelling tools SMARTFIRE and buildingEXODUS to the FSE based analysis database is currently not an automated process. Depending on the future requirements, this transfer can be automated but it will depend on enhancing SMARTFIRE and buildingEXODUS data export capabilities as mentioned previously.
- The expert interpretation of the analysis results is provided by the service provider. Currently, the overall conclusion, as well as the conclusion for each scenario is added in the database manually. However, an additional option can be added to the service provider interface which allows this information to be added through a web form.
- A successful test was conducted as indicated in Chapters 4 and 5 using a combination of an SQL query and additional code as part of a web service to calculate ASET value based on the fire hazard data in the FSE based analysis database. For this test, the ASET value was calculated by finding an average time value for all the zones when the specified tenability criteria were reached. As the ASET value can be calculated in several ways based on specified criteria, this process can be somewhat automated with multiple calculation options presented to the expert user.

- Key analysis output for various scenarios such as ASET/RSET values, exit usage and number evacuated/fatalities can be visually displayed on top of the building's Architecture model as a way of providing quick and easy access to important information.

Development of BIM-enabled prototype Smart Signage Management System based on the conceptual design presented in this study

The proposed conceptual design of the BIM-enabled Smart Signage Management System could be analysed and improved that can lead to the development of a prototype system as part of a potential future collaboration project. This is an area which FSEG may pursue.

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APPENDIX A: FSE relevant data support in IFC Model

The IFC Model has four conceptual layers. These layers adhere to the concept where elements of each layer can refer to the entities of their layer as well as of those in a lower layer. A brief description of the four layers based on the IFC4 documentation (buildingSMART, 2013) is given below:

Resource Layer: This lowest level layer has individual schemas containing resource definitions. These definitions do not include a Globally Unique Identifier (GUID). The elements of all other layers can reference the elements of this layer.

Core Layer: This layer is located above the Resource Layer. It contains the kernel and core extension schemas that have general entity definitions. Unlike the Resource Layer, the entities defined at this layer have GUIDs.

Interoperability Layer: This layer is located above the Core Layer. It has definitions which are specific to general product, process or resource specialisation. These are used for information sharing and inter-domain data exchange across various disciplines.

Domain Layer: This is the top layer which is located above the Interoperability Layer. The schemas in this layer have specialised discipline specific entity definitions of products, processes or resources. These are used for information sharing and intra-domain data exchange.

IFC 2x3

In IFC2x3 TC1, there are 117 Defined types, 164 Enumerations, 46 Select types, and 653 entities. The schema architecture of IFC 2x3 is shown in Figure A1 (buildingSMART, 2007).

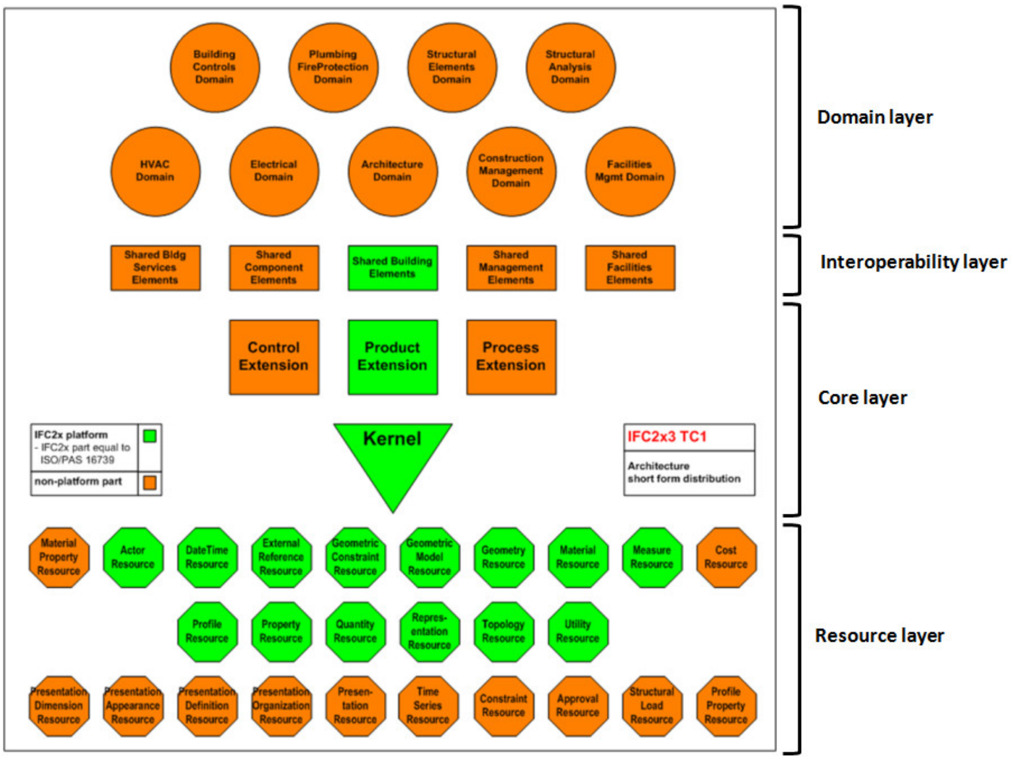

Figure A1: IFC2x3 Schema Architecture diagram (buildingSMART, 2007)

A detailed description of IFC 2x3 is available from (buildingSMART, 2007) so only very brief information is provided here for the purpose of clarity.

The schemas of IFC2x3 that are potentially relevant for FSE are shown in Figure A2 adapted from (buildingSMART, 2007).

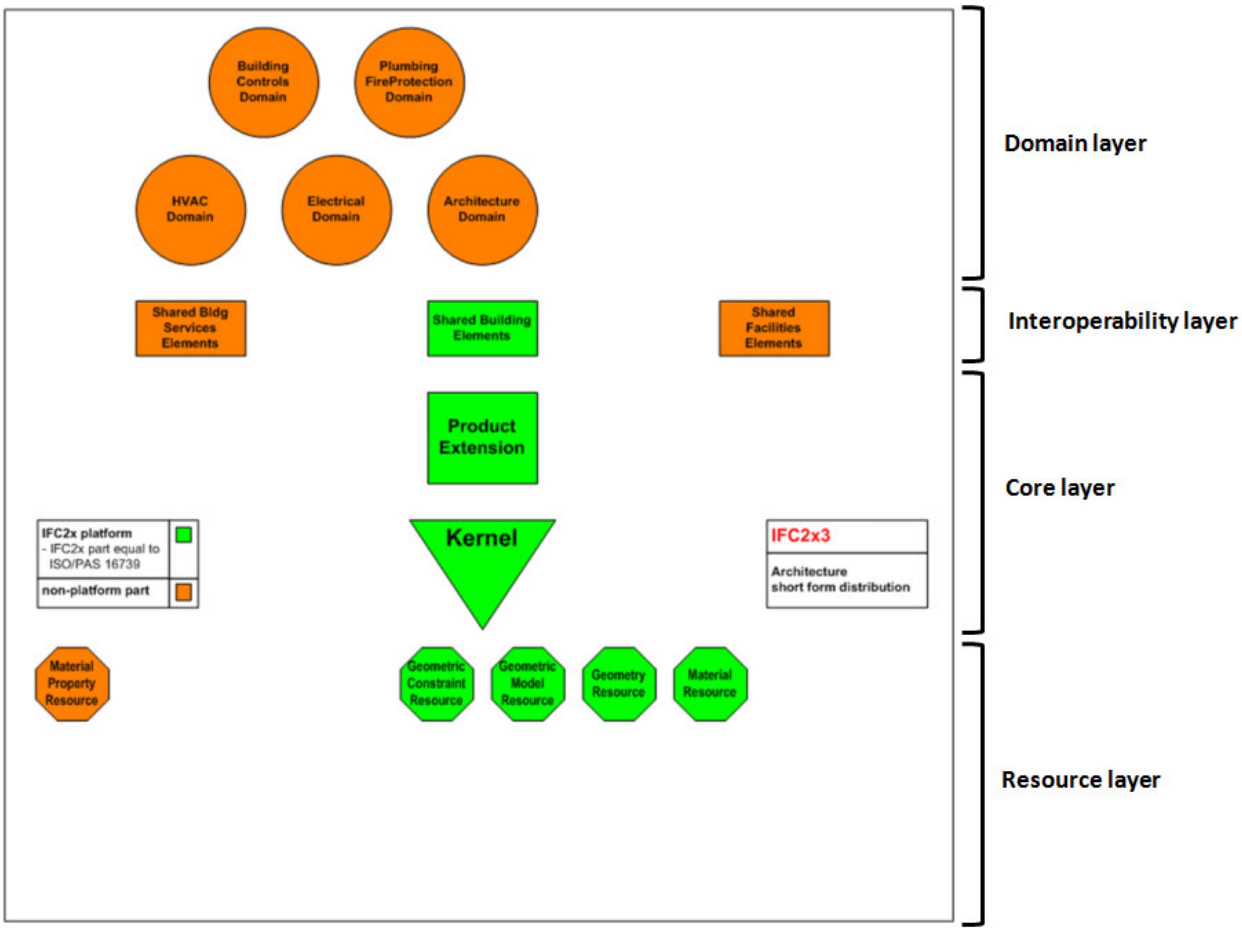

Figure A2: IFC2x3 Architecture diagram - only FSE relevant parts shown, adapted from (buildingSMART, 2007)

<u>In the Domain Layer</u>

- ***IfcBuildingControlsDomain:*** The concepts outlined in the *IfcSharedBldgServicesElements* schema are extended in this domain. The concepts defined in this domain are of building automation, control, instrumentation and alarm. The *IfcBuildingControlsDomain* has **5 Entities and 5 Enumerations.**
- ***IfcPlumbingFireProtectionDomain:*** The concepts outlined in the *IfcSharedBldgServicesElements* schema are extended in this domain. The concepts defined in this domain are of plumbing and fire protection. The *IfcPlumbingFireProtectionDomain* has **4 Entities and 4 Enumerations.**

- ***IfcHvacDomain:*** The concepts outlined in the *IfcSharedBldgServicesElements* schema are extended in this domain. The concepts defined in this domain are related to HVAC. The *IfcHvacDomain* has **31 Entities and 31 Enumerations.**
- ***IfcArchitectureDomain:*** The concepts defined in this domain are related to architecture. The *IfcArchitectureDomain* has **3 Entities and 1 Enumeration.**

- ***IfcElectricalDomain:*** The concepts outlined in the *IfcSharedBldgServicesElements* schema are extended in this domain. The concepts defined in this domain are of electrical supply and provision, concepts of light fixtures, etc. The *IfcElectricalDomain* has **19 Entities and 18 Enumerations**.

<u>In the Interoperability Layer</u>

- ***IfcSharedBldgElements***: The subtypes of *IfcBuildingElement* (in *IfcProductExtension)* are defined in this schema. These subtypes are major elements of the architectural design of a building structure. The *IfcSharedBldgElements* schema has **33 Entities and 22 Enumerations**.
- ***IfcSharedBldgServiceElements:*** The basic concepts needed for interoperability, mainly between Building Service domain extensions such as *IfcHvacDomain*, *IfcPlumbingFireProtectionDomain*, *IfcElectricalDomain,* and *IfcBuildingControlsDomain,* are defined in this schema. The *IfcSharedBldgServiceElements* schema has **30 Entities and 8 Enumerations.**

- ***IfcSharedFacilitiesElements:*** The basic concepts related to Facilities Management are defined in this schema. The *IfcSharedFacilitiesElements* schema has **8 Entities and 4 Enumerations**.

<u>In the Core Layer</u>

- ***IfcProductExtension:*** The concepts of component shape and placement within the project context are further specialised in this schema. The *IfcProductExtension* schema has **50 Entities and 9 Enumerations.**

- ***IfcKernal:*** The most abstract part of the IFC Model is defined in *IfcKernel*. It provides proxy definitions, type object definitions, and property set definitions. This allows *IfcKernel* to set the foundation of extensibility. The *IfcKernel* has **37 Entities, 1 Global Rule, 1 Function and 2 Enumerations**.

In the Resource Layer

- ***IfcMaterialPropertyResource:*** The types and classes which are used for material properties are defined in this schema. The *IfcMaterialPropertyResource* schema has **13 Entities.**
- ***IfcGeometricConstraintResource:*** The resources used to determine the placement of the shape representation of a product within the geometric representation context of a project are defined in this schema. The *IfcGeometricConstraintResource* schema has **11 Entities, 3 Select types and 1 Function.**
- ***IfcGeometricModelResource:*** The resources used for geometric model representations are defined in this schema. The *IfcGeometricModelResource* schema has **27 Entities, 3 Select types and 1 Enumeration**.
- ***IfcGeometryResource:*** The resources used for geometric representations are defined in the *IfcGeometryResource* schema. The *IfcGeometryResource* schema has **44 Entities, 1 Defined type, 3 Select types, 3 Enumerations and 19 Functions.**

IFC4

In IFC4, there are 766 entities. The schema architecture of IFC4 is shown in Figure A3 (buildingSMART, 2016b).

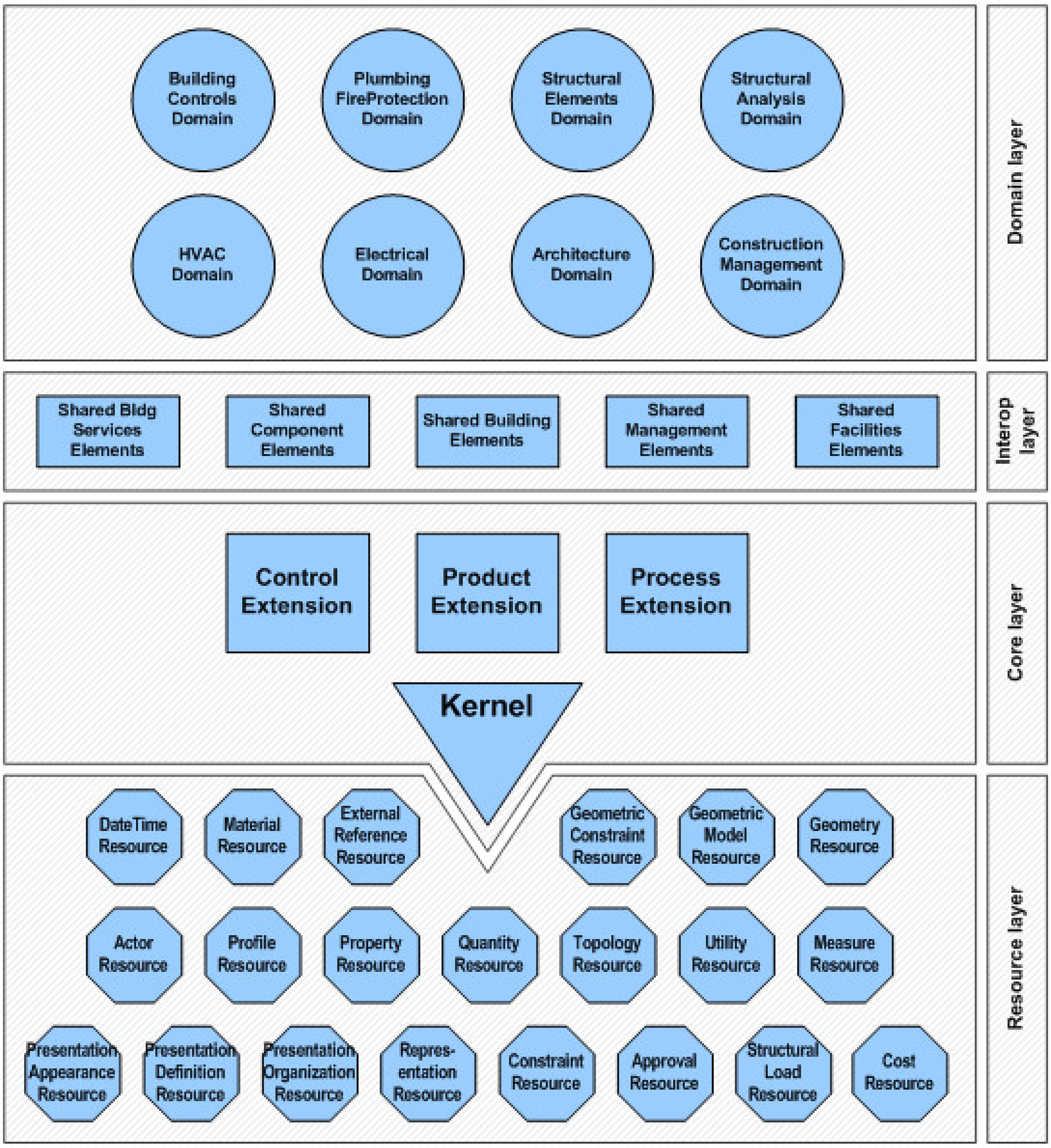

Figure A3: IFC4 Architecture diagram (buildingSMART, 2016b)

In IFC4, several changes have been made to the model. The number of entities and enumerations for each relevant model layer has already been covered for IFC2x3 but for IFC4 it is briefly mentioned below:

In the Domain Layer

- ***IfcBuildingControlsDomain:*** It has **12 Entities, 6 Enumerations, and 46 Property Sets**.
- ***IfcPlumbingFireProtectionDomain:*** It has **10 Entities, 5 Enumerations, and 25 Property Sets.**
- ***IfcHvacDomain:*** It has **66 Entities, 33 Enumerations, and 111 Property Sets**.
- ***IfcArchitectureDomain:*** It has **7 Entities and 9 Enumerations.**
- ***IfcElectricalDomain:*** It has **44 Entities, 22 Enumerations, and 80 Property Sets**.

In the Interoperability Layer

- ***IfcSharedBldgServiceElements:*** It has **26 Entities, 4 Enumerations, and 29 Property Sets**.
- ***IfcSharedBldgElements:*** It has **52 Entities, 23 Enumerations, and 24 Property Sets**.
- ***IfcSharedFacilitiesElements:*** It has **7 Entities, 4 Enumerations, and 17 Property Sets**.

In the Core Layer

- ***IfcProductExtension:*** It has **57 Entities, 14 Enumerations, and 44 Property Sets.**
- ***IfcKernal***: It has **50 Entities, 1 Defined Type, 1 Global Rule, 3 Functions, 1 Property Set, 5 Select Types, and 4 Enumerations**.

In Resource Layer

- ***IfcMaterialPropertyResource*** (Was part of the Resource Layer of the IFC2x3 Model). This is no longer included in IFC4.
- ***IfcGeometricConstraintResource:*** It has **11 Entities, 5 Select types and 1 Function.**
- ***IfcGeometricModelResource:*** It has **38 Entities, 4 Select types and 3 Functions**.
- ***IfcGeometryResource:*** It has **53 Entities, 10 Select types and 23 Functions.**

The parts of IFC4 that are potentially relevant for FSE are underlined and shown in Figure A4, adapted from (buildingSMART, 2016b).

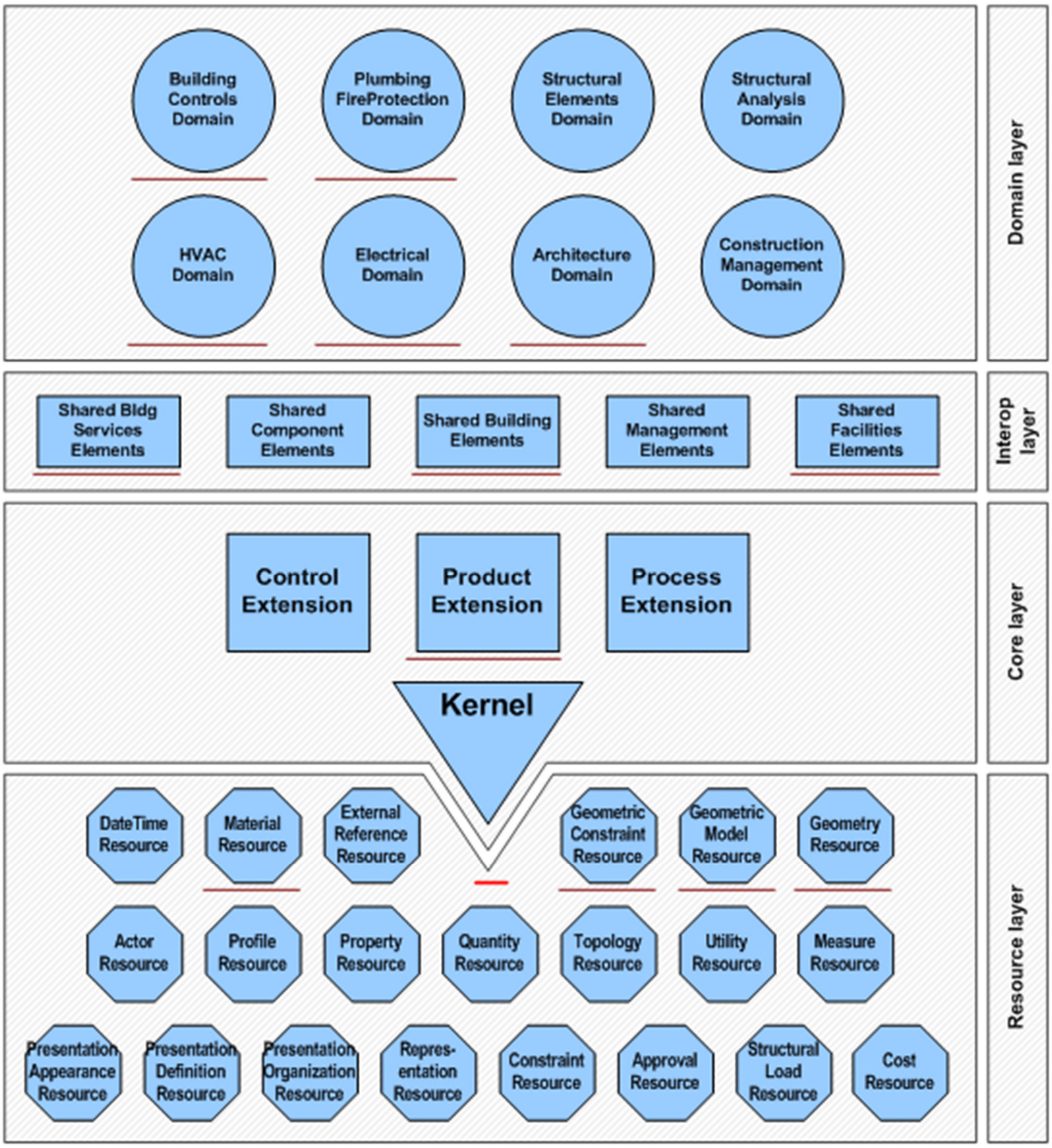

Figure A4: IFC4 Architecture diagram - FSE relevant parts underlined, adapted from (buildingSMART, 2016b)

A list of potentially FSE relevant schemas in the IFC Model and all their entities is shown in Tables A1, A2, A3, A4, A5, A6, A7, A8 and A9. It should be noted that not all the entities in each potentially FSE relevant schemas may be required. However, all the entities are still listed, with some of them in bold to highlight that they are more likely to be relevant for FSE. Also, not all the potentially FSE relevant schemas, as highlighted in Figure A2 and Figure A4, are covered in the tables mentioned above as they are related to geometry (e.g. *IfcGeometricConstraintResource*), *Kernel* (most abstract part of the IFC Model), and even the *IfcElectricalDomain* (may not be directly relevant to FSE).

The following colour scheme is used to provide an indication of the change from IFC 2x3 to IFC4: **Orange** for new entities, **Aqua** for entities moved from other parts of the IFC Model, **Dark Blue** for entities moved out to other parts of the IFC Model, and **Dark Red** for deleted entities.

Table A1: Entities in IFC2x3 and IFC4 - IfcBuildingControlsDomain

Schema name and IFC Model Layer	List of entities
IfcBuildingControlsDomain (Domain Layer) No. of entities: in IFC2x3 (5), in IFC4 (12)	*IfcActuatorType*, ***IfcAlarmType***, *IfcControllerType*, *IfcFlowInstrumentType*, ***IfcSensorType***, *IfcActuator*, ***IfcAlarm***, *IfcController*, *IfcFlowInstrument*, ***IfcSensor***, *IfcUnitaryControlElement*, *IfcUnitaryControlElementType*

Table A2: Entities in IFC2x3 and IFC4 - IfcPlumbingFireProtectionDomain

Schema name and IFC Model Layer	List of entities
IfcPlumbingFireProtectionDomain (Domain Layer) No. of entities: in IFC2x3 (4), in IFC4 (10)	***IfcFireSuppressionTerminalType***, *IfcSanitaryTerminalType*, *IfcStackTerminalType*, *IfcWasteTerminalType*, ***IfcFireSuppressionTerminal***, *IfcInterceptor*, *IfcInterceptorType*, *IfcSanitaryTerminal*, *IfcStackTerminal*, *IfcWasteTerminal*

Table A3: Entities in IFC2x3 and IFC4 - IfcHvacDomain

Schema name and IFC Model Layer	**List of entities**
IfcHvacDomain (Domain Layer) No. of entities: in IFC2x3 (31), in IFC4 (66)	***IfcAirTerminalBoxType***, ***IfcAirTerminalType***, *IfcAirToAirHeatRecoveryType, IfcBoilerType, IfcChillerType, IfcCoilType, IfcCompressorType, IfcCondenserType, IfcCooledBeamType, IfcCoolingTowerType,* ***IfcDamperType***, ***IfcDuctFittingType***, ***IfcDuctSegmentType***, ***IfcDuctSilencerType***, *IfcEvaporativeCoolerType, IfcEvaporatorType,* ***IfcFanType***, *IfcFilterType, IfcFlowMeterType, IfcHeatExchangerType, IfcHumidifierType, IfcPipeFittingType, IfcPipeSegmentType, IfcPumpType, IfcSpaceHeaterType, IfcTankType, IfcTubeBundleType, IfcUnitaryEquipmentType, IfcValveType, IfcVibrationIsolatorType,* ***IfcAirTerminal***, ***IfcAirTerminalBox***, *IfcAirToAirHeatRecovery, IfcBoiler, IfcBurner, IfcBurnerType, IfcChiller, IfcCoil, IfcCompressor, IfcCondenser, IfcCooledBeam, IfcCoolingTower,* ***IfcDamper***, ***IfcDuctFitting***, ***IfcDuctSegment***, ***IfcDuctSilencer***, ***IfcEngine***, ***IfcEngineType***, *IfcEvaporativeCooler, IfcEvaporator,* ***IfcFan***, *IfcFilter, IfcFlowMeter, IfcHeatExchanger, IfcHumidifier, IfcMedicalDevice, IfcMedicalDeviceType, IfcPipeFitting, IfcPipeSegment, IfcPump, IfcSpaceHeater, IfcTank, IfcTubeBundle, IfcUnitaryEquipment, IfcValve, IfcVibrationIsolator,* ~~*IfcGasTerminalType*~~

Table A4: Entities in IFC2x3 and IFC4 - IfcArchitectureDomain

Schema name and IFC Model Layer	**List of entities**
IfcArchitectureDomain (Domain Layer) No. of entities: in IFC2x3 (3), in IFC4 (7)	***IfcPermeableCoveringProperties***, ***IfcDoorLiningProperties***, ***IfcDoorPanelProperties***, ***IfcDoorStyle***, ***IfcWindowLiningProperties***, ***IfcWindowPanelProperties***, ***IfcWindowStyle***, ~~*IfcRelInteractionRequirements*, *IfcSpaceProgram*~~

Table A5: Entities in IFC2x3 and IFC4 - IfcSharedBldgElements

Schema name and IFC Model Layer	**List of entities**
IfcSharedBldgElements (Interoperability Layer) No. of entities: in IFC2x3 (33), in IFC4 (52)	***IfcBeam, IfcBeamType, IfcColumn, IfcColumnType, IfcCurtainWall, IfcCurtainWallType, IfcDoor, IfcMember, IfcMemberType, IfcPlate, IfcPlateType, IfcRailing, IfcRailingType, IfcRamp, IfcRampFlight, IfcRampFlightType, IfcRelConnectsPathElements, IfcRoof, IfcSlab, IfcSlabType, IfcStair, IfcStairFlight, IfcStairFlightType, IfcWall, IfcWallStandardCase, IfcWallType, IfcWindow, IfcBeamStandardCase, IfcBuildingSystem, IfcChimney, IfcChimneyType, IfcColumnStandardCase, IfcDoorStandardCase, IfcDoorType, IfcMemberStandardCase, IfcPlateStandardCase, IfcRampType, IfcRoofType,*** *IfcShadingDevice, IfcShadingDeviceType,* ***IfcSlabElementedCase, IfcSlabStandardCase, IfcStairType, IfcWallElementedCase, IfcWindowStandardCase, IfcWindowType,*** *IfcBuildingElementProxy, IfcBuildingElementProxyType, IfcCovering, IfcCoveringType,* ***IfcRelCoversBldgElements, IfcRelCoversSpaces,*** ~~***IfcDoorLiningProperties, IfcDoorPanelProperties, IfcDoorStyle, IfcWindowLiningProperties, IfcWindowPanelProperties, IfcWindowStyle***~~

Table A6: Entities in IFC2x3 and IFC4 - IfcSharedBldgServiceElements

Schema name and IFC Model Layer	**List of entities**
IfcSharedBldgServiceElements (Interoperability Layer) No. of entities: in IFC2x3 (30), in IFC4 (26)	*IfcDistributionChamberElement, IfcDistributionChamberElementType,* ***IfcDistributionControlElement****,* ***IfcDistributionControlElementType****,* ***IfcDistributionFlowElement****,* ***IfcDistributionFlowElementType****, IfcDistributionPort, IfcEnergyConversionDevice, IfcEnergyConversionDeviceType, IfcFlowController, IfcFlowControllerType, IfcFlowFitting, IfcFlowFittingType, IfcFlowMovingDevice, IfcFlowMovingDeviceType, IfcFlowSegment, IfcFlowSegmentType, IfcFlowStorageDevice, IfcFlowStorageDeviceType, IfcFlowTerminal, IfcFlowTerminalType, IfcFlowTreatmentDevice, IfcFlowTreatmentDeviceType, IfcRelFlowControlElements, IfcDistributionCircuit, IfcDistributionSystem,* ~~*IfcElectricalBaseProperties, IfcEnergyProperties, IfcFluidFlowProperties, IfcSoundProperties, IfcSoundValue, IfcSpaceThermalLoadProperties*~~

Table A7: Entities in IFC2x3 and IFC4 - IfcSharedFacilitiesElements

Schema name and IFC Model Layer	**List of entities**
IfcSharedFacilitiesElements (Interoperability Layer) No. of entities: in IFC2x3 (8), in IFC4 (7)	*IfcAsset*, ***IfcFurnitureType***, *IfcInventory*, *IfcOccupant*, ***IfcSystemFurnitureElementType***, ***IfcFurniture***, ***IfcSystemFurnitureElement***, ~~*IfcRelOccupiesSpaces*~~ ~~*IfcServiceLife, IfcServiceLifeFactor*~~

Table A8: Entities in IFC2x3 and IFC4 - IfcProductExtension

Schema name and IFC Model Layer	List of entities
IfcProductExtension (Core Layer) No. of entities: in IFC2x3 (50), in IFC4 (57)	*IfcAnnotation*, ***IfcBuilding***, ***IfcBuildingElement***, ***IfcBuildingElementType***, ***IfcBuildingStorey***, ***IfcDistributionElement***, ***IfcDistributionElementType***, ***IfcElement***, *IfcElementAssembly*, ***IfcElementQuantity***, ***IfcElementType***, *IfcFeatureElement*, *IfcFeatureElementAddition*, *IfcFeatureElementSubtraction*, ***IfcFurnishingElement***, ***IfcFurnishingElementType***, ***IfcGrid***, ***IfcOpeningElement***, *IfcPort*, *IfcProjectionElement*, *IfcRelAssociatesMaterial*, *IfcRelConnectsElements*, *IfcRelConnectsPortToElement*, *IfcRelConnectsPorts*, ***IfcRelConnectsWithRealizingElements***, ***IfcRelContainedInSpatialStructure***, ***IfcRelFillsElement***, ***IfcRelProjectsElement***, ***IfcRelReferencedInSpatialStructure***, ***IfcRelServicesBuildings***, ***IfcRelSpaceBoundary***, ***IfcRelVoidsElement***, ***IfcSite***, ***IfcSpace***, ***IfcSpaceType***, ***IfcSpatialStructureElement***, ***IfcSpatialStructureElementType***, ***IfcSystem***, ***IfcTransportElement***, ***IfcTransportElementType***, *IfcVirtualElement*, ***IfcZone***, *IfcCivilElement, IfcCivilElementType, IfcElementAssemblyType, IfcExternalSpatialElement, IfcExternalSpatialStructureElement, IfcGeographicElement, IfcGeographicElementType*, ***IfcOpeningStandardCase, IfcRelInterferesElements, IfcRelSpaceBoundary1stLevel, IfcRelSpaceBoundary2ndLevel, IfcSpatialElement, IfcSpatialElementType, IfcSpatialZone, IfcSpatialZoneType,*** ~~***IfcBuildingElementProxy, IfcBuildingElementProxyType, IfcCovering, IfcCoveringType, IfcRelCoversBldgElements, IfcRelCoversSpaces,***~~ ~~*IfcElectricalElement, IfcEquipmentElement*~~

Table A9: Entities in IFC2x3 and IFC4 - IfcMaterialPropertyResource

Schema name and IFC Model Layer	List of entities
IfcMaterialProperty Resource (Resource Layer) No. of entities: in IFC2x3 (13)	***IfcExtendedMaterialProperties***, ***IfcFuelProperties***, ***IfcGeneralMaterialProperties***, *IfcHygroscopicMaterialProperties*, ***IfcMaterialProperties***, *IfcMechanicalConcreteMaterialProperties*, *IfcMechanicalMaterialProperties*, *IfcMechanicalSteelMaterialProperties*, *IfcOpticalMaterialProperties*, ***IfcProductsOfCombustionProperties***, *IfcRelaxation*, ***IfcThermalMaterialProperties***, *IfcWaterProperties* Note: *IfcMaterialPropertyResource* has been removed in IFC4. *IfcMaterialProperties* entity has been moved to *IfcMaterialResource*.

APPENDIX B: Type and level of information supported by fire/evacuation modelling tools

In Appendix B, the following is covered:

- A basic overview of the type and level of information supported in four evacuation modelling tools (buildingEXODUS, MassMotion, Pathfinder and STEPS). This is included in Subsection B1.
- A basic overview of the type and level of information supported in two fire modelling tools (SMARTFIRE and PyroSim (GUI for FDS)). This is included in Subsection B2.
- Based on the review in Subsection B1, a detailed list of objects and their properties in the evacuation modelling tool buildingEXODUS is then presented in Subsection B3.
- Based on the review in Subsection B2, a detailed list of objects and their properties in the fire modelling tool SMARTFIRE is then presented in Subsection B4.
- Finally, the FSE based analysis preliminary database containing a list of tables and their fields are presented in Subsection B5. This database is mainly FSE output data focussed and covers a subset of the level of data presented in Subsection B3 and Subsection B4.

B1 Type and level of information captured by the evacuation modelling tools

To provide an indication of the level of information in terms of evacuation data including fire hazard impact, the following four tools were selected for a basic review as they are broadly representative examples of evacuation modelling as well as they have support for BIM IFC file import: buildingEXODUS (Galea, Lawrence, *et al.*, 2017), MassMotion (Oasys, 2017), STEPS (Mott MacDonald, 2016), and Pathfinder (Thunderhead Engineering, 2018b). It should be noted that the review does not focus on the geometry data. Table B1 provides an indication of the supported level of information in terms of evacuation related data in the four selected evacuation modelling tools. The type and level of information shown in Table B1 are based on the product manuals and it is only meant to provide a basic overview.

Table B1: Evacuation modelling tools type and level of support for evacuation data

	buildingEXODUS	**MassMotion**	**Pathfinder**	**STEPS**
Overall details	Simulation start time, Simulation end time, Total number of people, Number of males, Number of females, Number of people out, First person out time, Last person out time **Fire hazards related details** [Upper and Lower values for Hazard zone, Number of fatalities, First fatality time, Last fatality time]	Start time, Duration, Agent count, Events, Journey times, Origins, Destinations **Fire hazards related details** [capability not supported]	Start time, Run time, Total occupants, Min travel distance, Max travel distance, Average travel distance, Min exit time, Max exit time, Average exit time, Min finish time, Max finish time, Average finish time, Min refuge reach time, Max refuge reach time, Average refuge reach time **Fire hazards related details [**PLOT3D data output from FDS can be used by the Pathfinder. However, this is only for measurement and not for altering decision making or movements within the simulation.]	Start time, End time, Time step, Number of persons, Number of persons that left **Fire hazards related details** [Smoke data from Zone models and CFD simulations can be imported in STEPS. This smoke data can be represented visually using Isosurfaces and can affect walking speeds.]
Individual occupant level details	Occupant position in simulation, Gender, Age, Weight, Height, Agility, Mobility, Familiarity, Patience,	Agent ID, Age (amount of time the occupant has been in the simulation), Radius (Occupant's	ID, Gender, Priority Level, Shoulder Width, Shape, Height, Vehicle shape, Requires	Gender, Age, Awareness, Patience, Family name, Number people, Family

	buildingEXODUS	MassMotion	Pathfinder	STEPS
	Drive, Gene, Leader, Walk Speed, Fast Walk Speed, Crawl Speed, Up-Stair Speed, Down-Stair Speed, Up-Escalator Speed, Down-Escalator Speed, Response Time, Floor started, Start node, End node, Cumulative Waiting Time, Personal Elapsed Time, Personal Evacuation Efficiency, Distance travelled, Exit used, Signs used, Route taken, Itinerary list **Fire hazards related details** [Walk Respiratory minute volume (RMV), Fast Walk RMV, Rest RMV, Personal Incapacitation Dose, (FIH, FIN, FICO2, FIHc, FIHr, FIHCN, FICO, FIO2, VCO2)]*	size), Direction Bias, Movement, Speed, Tasks, Start floor, Position, Entrance, Exit, Start Time, End Time, Duration, State, Distance Travelled, Target, Route, End state	Assistance to Move, Initial Orientation, Ignore One-way Door Restrictions, Walk on Escalators, Restricted Components, Acceleration Time, Reduction Factor, Persist Time, Collision Response Time, Slow Factor, Wall Boundary Layer, Comfort Distance, Speed, Safe time total, Starting location, Follow Leader, Maximum Distance, Slowdown Time, Start time, Exit time, Finish time, Distance, Refuge reached time, Active time, Jam time max continuous, Jam time total **Fire hazards related details** [Can output FED for each occupant specified in cases where FDS PLOT3D output data is available for CO Volume Fraction, CO2 Volume	head, Walking speed, Pre-movement time, Journey Time - Total, Journey Time - Transit, Journey Stop Time, Free Movement Time, Delay Time, Time in Vehicles, Time in Lifts, Queuing Time, Journey Walking Speed, Movement Cost, Delay Cost, Total Cost, Journey Distance **Fire hazards related details** [The total accumulated exposure dose data for any toxic element can be exported from STEPS for each individual agent in the simulation.]

	buildingEXODUS	MassMotion	Pathfinder	STEPS
			Fraction, and O2 Volume Fraction.]	
Component usage level details	**Exit usage details** [several properties] **Internal Exit usage details** [several properties] **Stairway usage details** [several properties] **Lift usage details** [several properties] **Floor usage details** [several properties] **Escalator usage details** [several properties] **Travelator usage details** [several properties] **Gate usage details** [several properties] **Exit signage usage details** [several properties]	**Floor usage details** [several properties] **Escalator usage details** [several properties] **Ramp usage details** [several properties] **Zone usage details** [several properties]	**Exit usage details** [several properties] **Stairway usage details** [several properties] **Room usage details** [several properties]	**Exit usage details** [several properties] **Stairway usage details** [several properties] **Lift usage details** [several properties] **Floor usage details** [several properties] **Escalator usage details** [several properties] **Location usage details** [several properties] **Path usage details** [multiple properties] **Route usage details** [multiple properties]

	buildingEXODUS	**MassMotion**	**Pathfinder**	**STEPS**
	Corridor usage details [several properties] **Zone usage details** [several properties] **Census Region usage details** [several properties] **Census Line usage details** [several properties] **Congestion details** [several properties]			

* A FED toxicity model is used by buildingEXODUS to determine the impact of fire hazards on occupants. This model uses the assumption that the effects of certain fire hazards are related to the dose received rather than the exposure concentration. For these occupants, the model calculates the ratio of the dose received over time to the effective dose that causes incapacitation or death and sums these ratios during the exposure. The toxic effect is predicted to occur when the total reaches unity. The Hazard sub-model in buildingEXODUS controls the development of the atmospheric and physical environment. The atmospheric aspects comprise the distribution of the following: fire hazards CO2, CO, HCN, O2 depletion, Heat (radiative and conductive) and Smoke, and also the irritant gases HCl, HBr, HF, SO2, NO2, CH2CHO (Acrolein) and HCHO (Formaldehyde) (Galea, Lawrence, *et al.*, 2017).

B2 Type and level of information captured by the fire modelling tools

To provide an indication of the level of information in terms of fire data support in fire modelling tools, SMARTFIRE and PyroSim were reviewed as they are broadly representative examples of fire modelling as well as they have support for BIM IFC file import. This review is only meant to provide a basic overview. Also, the review does not focus on the geometry data. The information in Table B2 is based on the product manuals for SMARTFIRE (Ewer *et al.*, 2013) and PyroSim (Thunderhead Engineering, 2019).

Table B2: Type and level of support for fire data in fire modelling tools

	SMARTFIRE	**PyroSim (GUI for FDS)**
Material properties	Type, Name, general properties (several parameters), Surface properties (several parameters), Mode of Ignition (several parameters), Combustion properties (several parameters)]	Material Name, Material Type, Thermal Properties [several parameters], Pyrolysis [several parameters]
Smoke detection, warning and management	**Devices/Systems including their activation situation [**Fan, Nozzle)**].** Each device has its own set of parameters.	**Devices/Systems including their activation situation** [Gas or Solid Phase Device, Thermocouple, Flow Measurement, Heat Release Rate Device, Layer Zoning Device, Path Obscuration (Beam Detector) Device, Heat Detector, Smoke Detector, Sprinkler, Nozzle, HVAC Duct, HVAC Node, HVAC Fan, HVAC Filter, HVAC Aircoil, HVAC Vents] Each device/system has its own set of parameters.
Building Usage	**Fuels/fire sources [**Fire/Simple Fire (several parameters including position, size, start time,	**Surface types** [Adiabatic, Inert, Burner, Heater/Cooler, Supply,

	SMARTFIRE	PyroSim (GUI for FDS)
	end time], Multistage Fire (several parameters), Simple Heat (several parameters)]	Exhaust, Layered, Air Leak]. Each type has its own set of parameters.
Simulation output	**Output variables** [PRESSURE, U_VELOCITY, V_VELOCITY, W_VELOCITY, ENTHALPY, KINETIC_ENERGY, DISSIPATION_RATE, RADIATION_X_NEG, RADIATION_X_POS, RADIATION_Y_NEG, RADIATION_Y_POS, RADIATION_Z_NEG, RADIATION_Z_POS, SMOKE, EXTINCTION_COEFF, TEMPERATURE, BUOYANCY, ABSOPTION_COEFF, DENSITY, NEG_Z_MASS_FLUX, POS_Z_MASS_FLUX, NEG_X_MASS_FLUX, POS_X_MASS_FLUX, NEG_Y_MASS_FLUX, POS_Y_MASS_FLUX] Automatic function selections depending on the activation of physics sub-models [temp, o2, smoke, rad, co2, co, hcn, hcl]	**Simulation parameters categories** [Time, Output, Environment, Wind, Simulator, Radiation, Angled Geometry, Misc.]. Each category has its own set of parameters. **Output options** [Solid Profiles, 2D slices, 3D Slices, Boundary Quantities, Isosurfaces, Plot3D Data, Statistic]. Each output option has its own set of parameters.

The following should be noted about the SMARTFIRE simulation output approach:

- SMARTFIRE can be configured to output results data in several formats (e.g. VTU results file and/or incremental data save file, legacy VTK results file and/or incremental data file).
- In case of hazard sub-volume (or zone) approach, DAT file format (very similar to the CFAST data export file) is used. This hazard sub-volume (or zone) approach processes the numerical field data produced by SMARTFIRE to allow a sub-volume summary form of that data at each time step to be loaded into buildingEXODUS.
- The buildingEXODUS uses a sub-volume (or zonal) approach for the specification of hazard information. Also, the hazard information is only required at two characteristic heights (head height and crawl height).

The following should be noted about the FDS simulation output approach:

- In FDS, 3D datasets (Data3d) of gas-phase quantities can be output in Plot3d or 3D slice files.
- The Plot3d file format is compatible with other applications while the 3D slice approach is specific to FDS.
- Plot3d files always contain information for exactly five quantities while the 3D slices only have one quantity and only output exactly the quantities requested in the input file.
- Plot3d files contain data for exactly one time step but no animation information while 3D slice files contain animated data for all time steps.
- Plot3d files contain data for an entire mesh while 3D slices can be a subset of a mesh.

B3 Full list of data properties in evacuation modelling tool buildingEXODUS

Full list of data properties in evacuation modelling tool buildingEXODUS (uses Fine Network approach) is shown in Table B3. It is important to point out that some data values are static, but others are dynamic (i.e. may change one or more times during the simulation, e.g. changing usage of an exit at various times during the simulation). Even if some properties/attributes listed are of dynamic nature, the focus is on the initial input and the final output values. Also, for several properties/attributes, the range of values mentioned may also have an option for user defined value(s).

Table B3: Full list of data properties in evacuation modelling tool buildingEXODUS

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
Building Geometry	**Basic building components (e.g. Walls, Ceiling heights, Stairs and Lifts)**	**For Floor**			Supported by *IfcBuildingStorey*
		Title	Text		
		Floor to floor Height (in metres)	Number		
		For Corridor			Supported by *IfcSpace*
		Width	Number		
		Length	Number		
		For Zone			Basic aspects of a zone are supported by *IfcZone* and *IfcSpatialZone* Entities
		Zone name	Text		
		Zone type	Text	(Hazard, Response, Compartment, Visibility signs, Obstacle)	
		Zone nodes (list of node objects)	Object		
		Zone polygon (Polygon outline of the zone - series of coordinates)	Number		
		Zone area	Number		
		For Stairs			Supported by several Entities and their Property Sets (e.g. *IfcStair, IfcStairFlight, IfcStairFlightType, IfcStairType, IfcRailing, IfcRailingType*, etc.)
		Riser number	Number		
		Riser height (in metres)	Number		
		Tread depth (in metres)	Number		
		Nosing	Number		
		Handrail size (width of handrail)	Number		
		Horizontal length (in metres)	Number		
		Width (in metres)	Number		
		For Lift			Supported by several Entities and their Property Sets (e.g. *IfcTransportElement, IfcTransportElementType*, etc.)
		Width	Number		
		Depth (in metres)	Number		
		For Travelator			Supported by several Entities and their Property Sets (e.g.
		Width (in metres)	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Length (in metres)	Number		*IfcTransportElement, IfcTransportElementType*, etc.)
		For Gate			Supported by several Entities and their Property Sets (e.g. *IfcDoorTypeEnum, IfcDoorType, IfcDoor*, etc.)
		Width (in metres)	Number		
		Length (in metres)	Number		
		For Escalator			Supported by several Entities and their Property Sets (e.g. *IfcTransportElement, IfcTransportElementType*, etc.)
		Width (the physical width of the entire component)	Number		
		Height (vertical travel distance)	Number		
		Length (horizontal travel distance)	Number		
		Height of riser (in metres)	Number		
		Depth of tread (in metres)	Number		
	Vents (e.g. Doors and Windows)	**For Door**			Supported by several Entities and their Property Sets (e.g. *IfcDoorType, IfcDoor*, etc.)
		Width	Number		
	Fire safety related information (e.g. location of fire protection components and systems, load bearing indication for walls, etc.)	Not explicitly specified in buildingEXODUS			Supported by several Entities (e.g. *IfcAlarm, IfcFireSuppressionTerminal*, etc.)
Smoke detection, warning and management	**Fans, alarms and sprinklers activation situation**	Not specified in buildingEXODUS. However, Alarm activation situation can provide an indication of pre-movement times.			Supported by various Entities (e.g. *IfcAlarm*)
Building Usage	**Obstacles/ furniture in the building**	Furniture items can be presented as obstacles in buildingEXODUS			Supported by several Entities and their Property Sets (e.g. *IfcFurniture, IfcFurnitureType, Pset_FurnitureTypeCommon*)
	Number and distribution of occupants	Distribution	Text	(Uniform, Normal, Polynomial equation, Log Normal)	Occupancy information such as number of people for space/zone is supported by the Property Set *Pset_SpaceOccupancyRequirements* for *IfcSpace, IfcSpatialZone* and *IfcZone* Entities
	Occupants' characteristics and behaviour	**For individual occupant**			Not supported
		Gender	Text	(Male/Female)	
		Age (in years)	Number		
		Weight (in KG)	Number		
		Height (in metres)	Number		
		Agility	Number	(3 - 7)	
		Mobility	Number	(0 - 1.2)	
		Familiarity (list of exits)	Text		
		Patience (in seconds)	Number	(1 - 5)	

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Drive	Number	Male: (5 - 15), Female: (1 - 10)	
		Gene (a numerical ID used to identify a group)	Number		
		Leader	Boolean	Yes/No	
		Walk Speed (in m/sec)	Number	(0.72 - 1.35)	
		Fast Walk Speed (in m/sec)	Number	(0.80 - 1.5)	
		Crawl Speed (in m/sec)	Number	(0.16 - 0.30)	
		Up-Stair Speed (in m/sec)	Number		
		Down-Stair Speed (in m/sec)	Number		
		Up-Escalator Speed (in m/sec)	Number		
		Down-Escalator Speed (in m/sec)	Number		
		Response Time (in seconds)	Number	(0 - 30)	
		Walk RMV (in l/min)	Number	[(For Male: 23.75 - 26.25), (For Female: 21.38 - 23.63)]	
		Fast Walk RMV (in l/min)	Number	[(For Male 47.5 - 52.5), (For Female 42.25 - 47.25)]	
		Rest RMV (in l/min)	Number	[(For Male 8.075 - 8.925), (For Female 7.268 - 8.033)]	
		Personal Incapacitation Dose (PID) [in %]	Number	(5 - 45)	
		Position (occupant position in the simulation)	Number		
		Floor started	Number		
		Start node	Text		
		Itinerary (The occupant Itinerary List is made up from a number of pre-defined tasks that are to be performed prior to exiting the structure). This is basically a list of locations with optional associated information.			
	Escape routes	Not directly worked out/established.			Some indication can be gathered from the Property Set *Pset_SpaceFireSafetyRequirements* for *IfcSpace*, *IfcSpatialZone* and *IfcZone* Entities
	Signage	**For Exit Sign**			Supported by several Entities and their Property Sets (e.g. *IfcFurniture, IfcFurnitureType, Pset_FurnitureTypeCommon*)
		Title	Text		
		Width (in metres)	Number		
		Height from the ground (in metres)	Number		
		Type	Text	(Reflective, Self-illuminating)	
		Model - Visibility Termination Distance	Text	(User defined, NFPA, BS 5499-4:2000, BS 5266-7:1999)	
		Letter height (in metres)	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Termination distance (in metres)	Number		
		Colour	Text		
		Start X (in metres)	Number		
		Start Y (in metres)	Number		
		End X (in metres)	Number		
		End Y (in metres)	Number		
	Building occupancy at day/night time hours	Different population distributions and attributes to cater for different scenarios.			Information such as *OccupancyTimePerDay* for space/zone is supported by the Property Set *Pset_SpaceOccupancyRequirements* for *IfcSpace, IfcSpatialZone* and *IfcZone* Entities
Other Considerations	**Windows/Door failure changes ventilation**	Not explicitly supported in buildingEXODUS. However, this can be represented as a closed door i.e. an internal/external exit that has been damaged/remained open or closed, depending on the scenario.			This is for an expert user to establish based on the door information available from *IfcDoor* and related Entities and Property Sets.
Overall results (e.g. number of people safely out and number of fatalities/ casualties)		**For Overall Simulation**			Not supported
		Simulation start time	Number		
		Simulation end time	Number		
		Total number of people	Number		
		Number of males	Number		
		Number of females	Number		
		Number of people out	Number		
		First person out time	Number		
		Last person out time	Number		
		Number of fatalities	Number		
		First fatality time	Number		
		Last fatality time	Number		
		For Congestion			Not supported
		Congestion floor	Text		
		Congestion location (in x and y coordinates)	Number		
		Congestion duration (continuous period of congestion) [in seconds]	Number		
		Total Evacuation Time (TET) %	Number		
Component usage details (e.g. Usage of exits)		**For Zone usage**			Not supported
		Upper value (for Hazard zone)	Number		
		Lower value (For Hazard zone)	Number		
		For Exit usage			Not supported
		Exit name	Text		
		Direction	Text	(Forward, Reverse)	
		Potential	Number	(0 - any +ve number)	
		Attractiveness (in percentage)	Number	(0 - 100)	

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Unit Flow Rate (in occs/m/s)	Number		
		Usage type	Text	(General, Emergency)	
		Active	Boolean	Yes/No	
		Status	Text	(Open, Close)	
		Event times (a series of numbers indicating the door status change times) [in seconds]	Number		
		Number of occupants used it	Number		
		First exit (in seconds)	Number		
		Last exit (in seconds)	Number		
		Average Person Per Minute (PPM)	Number		
		Flow time (in seconds)	Number		
		No Flow time (in seconds)	Number		
		Optimal Performance Statistics (OPS)	Number		
		Mean Non-Flow Statistics (MNS)	Number		
		For Corridor usage			Not supported
		Lane width (in metres)	Number		
		Flow rate (in ppm)	Number		
		Total number of people	Number		
		First on (in sec)	Number		
		Last on (in sec)	Number		
		Catchment (in metres)	Number		
		For Internal Exit usage			Not supported
		Internal exit name	Text		
		Number out	Number		
		First exit (in seconds)	Number		
		Last exit (in seconds)	Number		
		Average Person Per Minute (PPM)	Number		
		Flow time (in seconds)	Number		
		No Flow time (in seconds)	Number		
		Mean Non-Flow Statistics (MNS)	Number		
		Potential	Number	(0 - any +ve number)	
		Unit Flow Rate (in occs/m/s)	Number		
		For Census Region usage			Not supported
		Census Point name	Text		
		Size	Number		
		Number through	Number		
		First in (in seconds)	Number		
		Last in (in seconds)	Number		
		Average Person Per Minute (PPM)	Number		
		Flow time (in seconds)	Number		
		No Flow time (in seconds)	Number		
		Mean Non-Flow Statistics (MNS)	Number		
		For Census Line usage			Not supported
		Census Line name	Text		
		Start X (in metres)	Number		
		Start Y (in metres)	Number		
		End X (in metres)	Number		
		End Y (in metres)	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Colour	Text		
		Number through	Number		
		First person to cross (in seconds)	Number		
		Last person to cross (in seconds)	Number		
		Average Person Per Minute (PPM)	Number		
		Flow time (in seconds)	Number		
		No Flow time (in seconds)	Number		
		Mean Non-Flow Statistics (MNS)	Number		
		Directional	Boolean	(Yes, No)	
		Length (in metres)	Number		
		Number of lanes	Number		
		Average Width (in metres)	Number		
		For Stairs usage			Not supported
		Staircase name	Text		
		Max capacity	Number		
		Number used it	Number		
		First used time (in seconds)	Number		
		Last used time (in seconds)	Number		
		Flow time (In seconds)	Number		
		Average flow rate (in persons per minute)	Number		
		Travel direction	Text		
		Handrail	Boolean	(Yes, No)	
		Number of lanes	Number		
		Lane width (in metres)	Number		
		Height (in metres)	Number		
		Catchment (in metres)	Number		
		Movement model	Text	(Flow, Individual)	
		Flow min (in people/m/s)	Number		
		Flow max (in people/m/s)	Number		
		Travel speed min (in m/s)	Number		
		Travel speed max (in m/s)	Number		
		Step Usage Model (a flag which relates to some default setting for Staggered or Packed, which are Pauls/Fruin or user defined)	Text	(Staggered, Packed)	
		For Lift usage			Not supported
		Lift name	Text		
		Start floor	Text		
		Status (Door status)	Text	(Open, Closed)	
		Capacity	Number		
		Start delay (The delay time before a lift begins servicing its floor sequence at the beginning of a simulation.)	Number		
		Is in service (if it is used within a simulation.)	Boolean	(Yes, No)	
		Max speed (in m/s)	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Acceleration (in m/s^2)	Number		
		Deceleration (in m/s^2)	Number		
		Opening time (in seconds)	Number		
		Closing time (in seconds)	Number		
		Dwell time (in seconds)	Number		
		Sensor adjusted dwell time (in seconds)	Number		
		Motor delay (in seconds)	Number		
		Sequence of floors (to service during an evacuation)			
		Numbers used it	Number		
		Number of trips made	Number		
		Total travel distance	Number		
		Average distance per trip	Number		
		Last person out time (in seconds)	Number		
		Lift occupant interaction (Each instance of when an occupant interacted with a lift using several fields of data)			
		For Floor usage			Not supported
		Floor name	Text		
		Number started (number of occupants started on this floor)	Number		
		Last exit time (in seconds)	Number		
		Min PET	Number		
		Max PET	Number		
		Average PET	Number		
		Min CWT	Number		
		Max CWT	Number		
		Average CWT	Number		
		CWT ratio	Number		
		Occupants floors times (experiences of occupants separated according to their start floor. The average amount of time occupants initially located on a given floor spent on each of the floors within the structure is provided, as is the average wait time of those occupants and the corresponding wait to time ratio.)			
		For Escalator usage			Not supported
		Title	Text		
		Travel direction	Text		
		Capacity	Number		
		Catchment (in metres)	Number		
		Number of lanes	Number		
		Lane capacity	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Lane width (The width of each lane which is derived from the width of the component and the number of Lanes) [in metres]	Number		
		Level run (The level/flat area at the end of the escalator) [in metres]	Number		
		Movement model	Text	(Flow, Individual)	
		Flow min - up (in people/m/s)	Number		
		Flow max - up (in people/m/s)	Number		
		Flow min - down (in people/m/s)	Number		
		Flow max - down (in people/m/s)	Number		
		Travel speed min - up (in m/s)	Number		
		Travel speed max - up (in m/s)	Number		
		Travel speed min - down (in m/s)	Number		
		Travel speed max - down (in m/s)	Number		
		Walkers	Number		
		Riders	Number		
		Walkers - Up (in %)	Number		
		Walkers - Down (in %)	Number		
		Riders - Up (in %)	Number		
		Riders - Down (in %)	Number		
		Rider bias	Text	(Right, Left, None)	
		Compliance (in %)	Number		
		Entry delay min - Male (in seconds)	Number		
		Entry delay max - Male (in seconds)	Number		
		Entry delay min - Female (in seconds)	Number		
		Entry delay max - Female (in seconds)	Number		
		Flow rate (in ppm)	Number		
		Total number of people	Number		
		First on (in sec)	Number		
		Last on (in sec)	Number		
		For Exit Signage usage			Not supported
		Sign ID	Text		
		Number of people used it	Number		
		Number of times the signage system was used	Number		
		Number of times occupants gave up and didn't follow the signs (for whole signage system)	Number		
		Number of people that used at least one sign (for whole signage system)	Number		
		Avg evac time of those who used a sign (for whole signage system)	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Avg evac time of those who saw at least one sign but did not use it (for whole signage system)	Number		
		For Ramp usage			Not supported
		No explicit support for ramps in buildingEXODUS			
		For Travelator usage			Not supported
		Title	Text		
		Travel direction	Text		
		Capacity	Number		
		Catchment (in metres)	Number		
		Number of lanes	Number		
		Lane capacity	Number		
		Lane width (The width of each lane which is derived from the width of the component and the number of Lanes) [in metres]	Number		
		Movement model	Text	(Flow, Individual)	
		Flow min - up (in people/m/s)	Number		
		Flow max - up (in people/m/s)	Number		
		Flow min - down (in people/m/s)	Number		
		Flow max - down (in people/m/s)	Number		
		Travel speed min - up (in m/s)	Number		
		Travel speed max - up (in m/s)	Number		
		Travel speed min - down (in m/s)	Number		
		Travel speed max - down (in m/s)	Number		
		Walker percentage	Number		
		Rider bias	Text	(Right, Left, None)	
		Compliance (in %)	Number		
		Entry delay min - Male (in seconds)	Number		
		Entry delay max - Male (in seconds)	Number		
		Entry delay min - Female (in seconds)	Number		
		Entry delay max - Female (in seconds)	Number		
		Flow rate (in ppm)	Number		
		Total number of people	Number		
		First on (in sec)	Number		
		Last on (in sec)	Number		
		For Gate usage			Not supported
		Title	Text		
		Travel direction	Text		
		Capacity	Number		
		Catchment (in metres)	Number		
		Number of lanes	Number		
		Lane capacity	Number		

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Lane width (The width of each lane which is derived from the width of the component and the number of Lanes) [in metres]	Number		
		Movement model	Text	(Flow, Individual)	
		Flow min - up (in people/m/s)	Number		
		Flow max - up (in people/m/s)	Number		
		Flow min - down (in people/m/s)	Number		
		Flow max - down (in people/m/s)	Number		
		Travel speed min - up (in m/s)	Number		
		Travel speed max - up (in m/s)	Number		
		Travel speed min - down (in m/s)	Number		
		Travel speed max - down (in m/s)	Number		
		Walker percentage	Number		
		Rider bias	Text	(Right, Left, None)	
		Compliance (in %)	Number		
		Entry delay min - Male (in seconds)	Number		
		Entry delay max - Male (in seconds)	Number		
		Entry delay min - Female (in seconds)	Number		
		Entry delay max - Female (in seconds)	Number		
		Flow rate (in ppm)	Number		
		Total number of people	Number		
		First on (in sec)	Number		
		Last on (in sec)	Number		
Individual occupant level details		**Individual occupant simulation data**			Not supported
		End node	Text		
		Exit used	Text		
		Distance travelled (in metres)	Number		
		Cumulative Waiting Time (CWT) [in seconds]	Number		
		Personal Elapsed Time (PET) [in seconds]	Number		
		Personal Evacuation Efficiency (PEE) [1 - CWT/PET]	Number		
		Sign(s) used (this is for occupant's use of signage system i.e. the sign(s) used by an occupant)			

Data category	Subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Route (provides information on the Internal Exits, Census Nodes and exits that an occupant has visited during the simulation. Also, occupant's time of arrival at that specific location.)			
		Itinerary details (several attributes providing information about the list of tasks in the itinerary and their outcome)			
		FIH	Number		
		FIN	Number		
		FICO2	Number		
		FIHc	Number		
		FIHr	Number		
		FIHCN	Number		
		FICO	Number		
		FIO2	Number		
		VCO2	Number		
		FIC MAX	Number		
		FIC	Number		
		FLD	Number		
		TF	Number		
		CD	Number		
		FIC CIIF	Number		

B4 Full list of data properties in fire modelling tool SMARTFIRE

The SMARTFIRE software suite has the following four main logical components: a scenario designer, a front-end case specification environment, an automated interactive meshing system, and a CFD numerical engine. The Scenario Designer and the Case Specification Environment provide very different modes of interaction that can be better suited to a particular type of problem. It should be noted that the Scenario Designer cannot perform all of the tasks of the Case Specification Environment, so it will still be necessary for the Scenario Designer geometry to be loaded into the Case Specification Environment, Configured and then Meshed before the CFD simulation can be performed. The Scenario Designer system facilitates a building model to be constructed from a CAD floor plan. Scenarios for simulation with SMARTFIRE can then be generated by selecting and adding the required objects to the building model. Once a scenario has been exported, the user will need to configure the simulation options, physics activation and create a mesh of control volumes (in the SMARTFIRE Case Specification Environment) before the scenario can be simulated (Ewer *et al.*, 2013).

In SMARTFIRE there are several sub-models which can be used in a particular CFD simulation. The following is an indication of what sub-models are needed and/or run in a particular CFD simulation: HEAT (always), FLOW (always), TURBULENCE (always), COMBUSTION (sometimes), SMOKE (usually), THERMAL RADIATION (usually on), TOXICITY (sometimes), WATER DROPLETS TRACKING i.e. SPRINKLER (sometimes). By using the 'Problem type options' menu in SMARTFIRE, these sub-models can be activated or by required variables or object features, which would imply certain sub-models would be needed. For example, sprinklers => needs water droplets tracking, combustion fire source => needs combustion, fan => needs flow and turbulence, sensor alarm => needs smoke and/or heat, occupant exposure simulation (as output) => needs toxicity, smoke, heat, thermal radiation.

Full list of data properties in fire modelling tool SMARTFIRE is shown in Table B4. It is important to point out that some data values are static, but others are dynamic (i.e. may change one or more times during the simulation). Even if some properties/attributes listed are of dynamic nature, the focus is on the initial input and the final output values. Also, for several properties/attributes, the range of values mentioned may also have an option for user defined value(s).

Colour scheme: Object available in SMARTFIRE Scenario Designer, Object available in SMARTFIRE Case Specification Environment, and Object available in both SMARTFIRE Scenario Designer and Case Specification Environment.

Table B4: Full list of data properties in fire modelling tool SMARTFIRE

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
Building Geometry	**Basic building components (e.g. Walls, Ceiling heights, Stairs and Lifts)**	**For Storey**			Supported by *IfcBuildingStorey*
		Position (x and z coordinates)	Number		
		Size (x and z directions)	Number		
		Height	Number		
		Ceiling/Floor Depth (Thickness of the ceiling/floor block above the storey)	Number		
		Ceiling/Floor Material (Material used for the ceiling/floor block)	Text		
		Wall Material [(Rooms) - Material used for the external region outer walls]	Text		
		For Wall			Supported by several Entities and their Property Sets (e.g. *IfcWall, IfcWallType, Pset_WallCommon*)
		Name	Text		
		Material	Text		
		Thickness	Number		
		Emissivity	Number		
		Wall / Flow handling	Text	(Wall, Symmetry)	
		Heat/Temp handling	Text	[(Non conducting wall), (Conducting wall), (Default wall temperature), Prescribed wall temperature (value in K), Prescribed Heat Flux (value in kW)]	
		For Partition (can be used to create a thin wall within a room and is exported to SMARTFIRE as a thin plate)			Can be supported by several Entities and their Property Sets (e.g. (*IfcWall, IfcWallType*)
		Start (in x and z coordinates)	Number		
		End (in x and z coordinates)	Number		
		Elevation	Number		
		Height	Number		
		Length	Number		
		Attach To Ceiling	Boolean	(Yes, No)	
		Attach To Floor	Boolean	(Yes, No)	
		Material	Text		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		For Thin Plate (a solid boundary patch with a default thickness and reference material type)			Supported by several Entities and their Property Sets (e.g. *IfcPlate, IfcPlateType, Pset_PlateCommon*)
		Name	Text		
		Material	Text		
		Heat/Temp handling	Text	[(Non conducting wall), (Conducting wall), (Default wall temperature), Prescribed wall temperature (value in K), Prescribed Heat Flux (value in kW)]	
		Thickness	Number		
		Face tile fail	Boolean	(Yes, No)	
		Face tile fail temperature (K)	Number		
		For Burnable Thin Plate			Supported by several Entities and their Property Sets (e.g. *IfcPlate, IfcPlateType, Pset_PlateCommon*)
		Similar to Thin Plate with ignition and burning behaviour defined by the material.			
		For Room			*IfcSpace* and *IfcRelSpaceBoundary* Entities and associated Property Sets can be used for this
		Position (x and z coordinates)	Number		
		Dimension (x and z sizes)	Number		
		Has Ceiling	Boolean	(Yes, No)	
		For Zone/Hazard Sub-Volume			Basic aspects of a zone are supported by *IfcZone* and *IfcSpatialZone* Entities
		Zone ID	Number		
		X-High - Coordinate	Number		
		X-Low - Coordinate	Number		
		Y-High - Coordinate	Number		
		Y-Low - Coordinate	Number		
		Z-High - Coordinate	Number		
		Z-Low - Coordinate	Number		
		Upper Layer - Y-High (in metres)	Number		
		Upper Layer - Y-Low (in metres)	Number		
		Lower Layer - Y-High (in metres)	Number		
		Lower Layer - Y-Low (in metres)	Number		
		For Staircase			Supported by several Entities and their Property Sets (e.g. *IfcStair, IfcStairFlight, IfcStairFlightType, IfcStairType, IfcRailing, IfcRailingType*)
		Position (x and z coordinates)	Number		
		Size (x and z directions)	Number		
		Elevation	Number		
		Height	Number		
		Width	Number		
		Number of stairs	Number		
		Orientation	Number		
		Style	Text		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Attach To Ceiling	Boolean	(Yes, No)	
		Attach To Floor	Boolean	(Yes, No)	
		Material	Text		
	Vents (e.g. Doors and Windows)	**For Door**			Supported by several Entities and their Property Sets (e.g. *IfcDoorType, IfcDoor*)
		Position (x and z positions coordinates)	Number		
		Elevation	Number		
		Width	Number		
		Height	Number		
		Type	Text	(Door, Window)	
		State	Text	(Open, Closed)	
		Material	Text		
		For Window			Supported by several Entities and their Property Sets (e.g. *IfcWindow, IfcWindowType, Pset_WindowCommon*)
		Position (x and z positions coordinates)	Number		
		Elevation	Number		
		Width	Number		
		Height	Number		
		Type	Text	(Door, Window)	
		State	Text	(Open, Closed)	
		Material	Text		
		For Ceiling Opening (when this is exported to SMARTFIRE, either a vent or a portal is created)			Can be supported by *IfcOpeningElement*
		Position (x and z positions coordinates)	Number		
		Size (x and z directions)	Number		
		For Vent (can represent any opening to the outside such as a door or window which is assumed to be naturally ventilated)			Can be supported by several Entities (e.g. *IfcOpeningElement*)
		Name	Text		
		Material	Text		
		For Aperture (a hole in a thin plate)			Can be supported by several Entities (e.g. *IfcOpeningElement*)
		Name	Text		
		Material	Text		
		For Inlet			This is for an expert user to establish based on the type of object.
		X (X position coordinate)	Number		
		Z (Z position coordinate)	Number		
		Elevation	Number		
		Width	Number		
		Height	Number		
		X Size	Number		
		Z Size	Number		
		Name	Text		
		Temperature (in K)	Number		
		Flow rate (in m^3/s)	Number		
		U-Velocity (m/s)	Number		
		V-Velocity	Number		
		W-Velocity	Number		
		Kinetic Energy	Number		
		Dissipation Rate	Number		
		Fuel fraction in inlet	Number		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Mixture fraction in inlet	Number		
		Gas Species fraction in inlet	Number		
		Auto Calculate Turbulence	Boolean	(Yes, No)	
		Internal Inlet	Boolean	(Yes, No)	
		For Outlet (a free surface that will allow flow in both inward and outward directions)			This is for an expert user to establish based on the type of object.
		X (X position coordinate)	Number		
		Z (Z position coordinate)	Number		
		Elevation	Number		
		Width	Number		
		Height	Number		
		X Size	Number		
		Z Size	Number		
		Name	Text		
		Pressure (in Pa)	Number		
		Temperature (in K)	Number		
		For Fixed Pressure Surface (has a prescribed pressure value and will allow flow in both inward and outward directions)			This is for an expert user to establish based on the type of object.
		Name	Text		
		Pressure (in Pa)	Number		
		Temperature (in K)	Number		
		For Portal (a doorway or opening through an obstacle)			Can be supported by several Entities (e.g. *IfcOpeningElement*)
		Name	Text		
		Material	Text		
		Opening direction	Text	(X-direction, Y-direction, Z-direction)	
		Initial temperature	Number		
	Fire safety related information (e.g. location of fire protection components and systems, load bearing indication for walls, etc.)	This can include coordinates (X1, Y1, Z1) to (X2, Y2, Z2). In SMARTFIRE, Y is the height above the floor.			Supported by various Entities (e.g. *IfcAlarm*, *IfcFireSuppressionTerminal*)
Material Properties	**Thermo-physical properties of building structural components, fire rating indication**	**For Material**			Supported by several Entities and their Property Sets (e.g. *IfcMaterial*, *Pset_MaterialCommon*, *Pset_MaterialFuel*)
		Type	Text		
		Name	Text		
		Num objects used in	Number		
		Built-in	Boolean	(Yes, No)	
		Conductivity (in W m^-1 K^-1)	Number		
		Specific heat (in J kg^-1 K)	Number		
		Density (in kg m^-3)	Number		
		Laminar viscosity (in Pa s)	Number		
		Thermal expansion coeff (in K ^-1)	Number		
		Molecular weight (in kg kmol^-1)	Number		
		Use HCL absorption	Boolean	(Yes, No)	
		HCL Coeff 1	Number		
		HCL Coeff 2	Number		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		HCL Coeff 3	Number		
		HCL Coeff 4	Number		
		HCL Coeff 5	Number		
		HCL Coeff 6	Number		
		HCL Coeff 7	Number		
		Use Gas Species absorption	Boolean	(Yes, No)	
		Deposition area modifier	Number		
		Deposition rate coefficient	Number		
		Max surface concentration (in kg m^-2)	Number		
		Max deposition temperature (in K)	Number		
		Partition Coefficient	Number		
		Ignition by surface flame spread	Boolean	(Yes, No)	
		Upward rate (in m s^-1)	Number		
		Upward angle (in deg)	Number		
		Downward rate (in m s^-1)	Number		
		Downward angle (in deg)	Number		
		Ignition by critical surface temperature	Boolean	(Yes, No)	
		Ignition temperature (in K)	Number		
		Ignition by Gas flame	Boolean	(Yes, No)	
		Flame temperature (in K)	Number		
		Time before ignition (in sec)	Number		
		Ignition by radiative heat flux	Boolean	(Yes, No)	
		Ignition heat flux (in W m^-2)	Number		
		Time before ignition [Heat flux (in sec)]	Number		
		Use heat release rate	Boolean	(Yes, No)	
		Heat release rate (in W m^-2)	Number		
		Use fuel mass loss rate	Boolean	(Yes, No)	
		Fuel mass loss rate (in kg s^-1 m^-2)	Number		
		Use smoke release rate	Boolean	(Yes, No)	
		Smoke release rate (in kg s^-1 m^-2)	Number		
		Use HCL release rate	Boolean	(Yes, No)	
		HCL release rate (in kg s^-1 m^-2)	Number		
Smoke detection, warning and management	**Fans, alarms and sprinklers activation situation**	**For Fan**			Supported by several Entities and their Property Sets (e.g. *IfcFan, IfcFanType, Pset_FanTypeCommon, Pset_FanOccurrence*)
		X (X position coordinate)	Number		
		Z (Z position coordinate)	Number		
		X Size	Number		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Z Size	Number		
		Elevation	Number		
		Height	Number		
		Area	Number		
		Blowing direction	Text	[X(+), X(-), Y(+), Y(-), Z(+), Z(-)]	
		Start time	Number		
		End time	Number		
		Terminate at end	Boolean	(Yes, No)	
		For Simple Fan (similar to a Fan except that it does not link the flow speed to the Pressure Difference across the fan)			Supported by several Entities and their Property Sets (e.g. *IfcFan, IfcFanType, Pset_FanTypeCommon, Pset_FanOccurrence*)
		Name	Text		
		Fan velocity	Number		
		Coeff Value	Number		
		Blowing direction	Text	[X(+), X(-), Y(+), Y(-), Z(+), Z(-)]	
		Start time	Number		
		End time	Number		
		Terminate at end	Boolean	(Yes, No)	
		For Nozzle			Supported by several Entities and their Property Sets (e.g. *IfcFireSuppressionTerminal, Pset_FireSuppressionTerminal-TypeCommon, Pset_FireSuppressionTerminal-TypeSprinkler*, etc.)
		Name	Text		
		Is active	Boolean	(Yes, No)	
		Using	Text	(Randomized Trajectory Settings, Fixed Trajectory Settings)	
		Trajectories	Number		
		Orientation normal (in x y z)	Number		
		Angle	Number		
		Speed	Number		
		Cone type	Text	(Hollow cone, Solid cone)	
		Angle min	Number		
		Angle max	Number		
		Temperature (in K)	Number		
		Flow rate (in kg/s)	Number		
		Initial speed (m/s)	Number		
		Droplet offset (in m)	Number		
		Droplet group index	Number		
		OF Number of Droplet Groups	Number		
		Droplet diameter (m)	Number		
		Normalized frequency	Number		
		Fixed trajectory index	Number		
		N. Parts	Number		
		Diameter (in m)	Number		
		Temperature (in K)	Number		
		Position (x y z in m)	Number		
		U (in m/s)	Number		
		V (in m/s)	Number		
		W (in m/s)	Number		

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
Building Usage	Fuels i.e. burnable items/fire sources in the building	**For Fire/Simple Fire**			Fire safety related information for space/zone (e.g. an indication for *FireRiskFactor* and *FlammableStorage*) is supported by the Property Set *Pset_SpaceFireSafetyRequirements* for *IfcSpace, IfcSpatialZone and IfcZone* Entities Based on the type and material, burnable items can be identified Fire type and related properties not supported
		X (X position coordinate)	Number		
		Z (Z position coordinate)	Number		
		Elevation	Number		
		X Size	Number		
		Z Size	Number		
		Height	Number		
		Type (Read-only)	Text	(Simple Fire)	
		Name	Text		
		Heat release curve type	Text	[(Constant, Simple, Expert, Standard fires (SLOW, MEDIUM, FAST, ULTRA-FAST), Table defined)]	
		A [constant heat release coefficient (in kW)]	Number		
		B [heat release coefficient with linear time (in kWs^{-1})]	Number		
		C [heat release coefficient with t^2 (in kWs^{-2})]	Number		
		D [exponential heat release coefficient (in kW)]	Number		
		E [exponential term modifier with linear time (in S^{-1})]	Number		
		Start time	Number		
		End time	Number		
		Terminate at end time	Boolean	(Yes, No)	
		Peak fire output (in kW)	Number		
		Total heat output (in MJ)	Number		
		Max rate of heat rise (in k W/s)	Number		
		Average heat output (in kW)	Number		
		Peak smoke output (in kg/s)	Number		
		Total smoke (in kg)	Number		
		For Multistage Fire			Not supported
		Three stage Fire definitions using standard curves for the growth, sustained and decay period of fire development.			
		For Simple Heat			Not supported

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Similar to Fire but only outputs heat even if the case includes combustion fires. This allows mixed mode fire modelling with combustion and Heat Release Rate (HRR) fires.			
	Obstacles/furniture in the building	**For Obstacle**			Supported by several Entities and their Property Sets (e.g. *IfcFurniture, IfcFurnitureType, Pset_FurnitureTypeCommon*)
		Name	Text		
		Position (x and z coordinates)	Number		
		Size (x and z directions)	Number		
		Material	Text		
		Initial temperature	Number		
		For Block (a solid rectangular obstruction)			Supported by *IfcBlock*
		Position (x and z coordinates)	Number		
		Size (x and z directions)	Number		
		Elevation	Number		
		Height	Number		
		Attach To Ceiling	Boolean	(Yes, No)	
		Attach To Floor	Boolean	(Yes, No)	
		Material	Text		
		For Volume Porosity			This is for an expert user to establish and model in a fire modelling tool.
		Name	Text		
		Volume porosity	Number	(0.0 - 1.0)	
	Building occupancy at day/night time hours	This may have some implications for where hazard data is needed for export.			Information such as *OccupancyTimePerDay* for space/zone is supported by the Property Set *Pset_SpaceOccupancyRequire-ments* for *IfcSpace*, *IfcSpatialZone* and *IfcZone* Entities
Other Considerations	**Windows/Door failure changes ventilation**	Handled as triggered or timed changes (can be repeated) to the Thin plates that block Portals or door openings (gaps in walls).			This is for an expert user to establish based on the door/window information available from *IfcDoor*, *IfcWindow* and related Entities and Property Sets.
	Leakages	**For Door (leakages)**			This is for an expert user to establish based on the door information available from *IfcDoor* and related Entities and Property Sets.
		Leaky (Models a leakage at the base of a door)	Boolean	(Yes, No)	
		CFD Leakage Area Height (Leakage height in CFD mesh)	Number		
		Actual Leakage Height (Leakage height in geometry)	Number		
		Leakage Area Porosity (Read-only property)	Number	(0.0 to 1.0)	

<table>
<tr><th>Data category</th><th>Data subcategory</th><th>Attribute/Property</th><th>Data type</th><th>Range of values</th><th>Support in BIM IFC Model</th></tr>
<tr><td rowspan="12"></td><td rowspan="12">Behaviour of the components (e.g. alarm activation conditions and sprinkler performance/ activation)</td><td colspan="3">Activation data for Thin Plate/Burnable Thin Plate/Inlet/Outlet/Fixed Pressure Surface/Fan/Simple Fan/Nozzle/Fire/Simple Fire/Obstacle</td><td rowspan="6">This can be established by an expert user by checking the properties of relevant components as they can provide an indication. For instance, IfcPlate, IfcPlateType, Pset_PlateCommon</td></tr>
<tr><td>Activation</td><td>Text</td><td>(ALWAYS ACTIVE, ALWAYS INACTIVE, ACTIVE FROM START, ACTIVE UNTIL END, ACTIVE BETWEEN TIMES, INACTIVE BETWEEN TIMES, ACTIVATED BY TRIGGER, DE-ACTIVATED BY TRIGGER)</td></tr>
<tr><td>Activation start time</td><td>Number</td><td></td></tr>
<tr><td>Activation end time</td><td>Number</td><td></td></tr>
<tr><td>Triggered by</td><td>Text</td><td></td></tr>
<tr><td>Critical change</td><td>Boolean</td><td>(Yes, No)</td></tr>
<tr><td colspan="3">Trigger Cell/ Trigger Volume (It allows an activation/deactivation event to be performed when a specified simulation state has been reached)</td><td rowspan="5">This can be established by an expert user by checking the properties of relevant components as they can provide some indication.</td></tr>
<tr><td>Name</td><td>Text</td><td></td></tr>
<tr><td>Up to 8 separate tests may be performed for trigger activation. Test properties include: Trigger variable, Activate when, Trigger value, Active.</td><td></td><td></td></tr>
<tr><td>Combine condition tests using (These tests can be combined using 'AND', i.e. all must be satisfied to allow the activation, or 'OR', i.e. any one condition satisfied will allow the activation)</td><td>Text</td><td>(AND, OR)</td></tr>
<tr><td>Delay activation time by</td><td>Number</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Fire simulation data (e.g. Smoke and heat distribution)</td><td rowspan="3"></td><td colspan="3">General simulation settings (only some options included here)</td><td rowspan="3">Not supported</td></tr>
<tr><td>Module to activate (SMARTFIRE sub-models required for a particular simulation can be activated using this option)</td><td></td><td></td></tr>
<tr><td>Time step size (in seconds)</td><td>Number</td><td></td></tr>
</table>

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		Number of steps	Number		
		Convergence tolerance	Number		
		Sweeps per time step	Number		
		Total simulation time (in seconds)	Number		
		Output for Zone/Hazard Sub-Volumes			Not supported
		Temperature (in Kelvin)	Number		
		Oxygen (in %)	Number		
		Smoke (in m^{-1})	Number		
		Radiation (in W/m^2)	Number		
		CO (in ppm)	Number		
		CO_2 (in %)	Number		
		HCN (in ppm)	Number		
		HCL (in ppm)	Number		
		Hazard visualisation (SMARTFIRE saves VTK and WRL format files for field data and the intermediate geometry, respectively. This could then cover alternative formats such as Cut Planes and the Zone data visualisation format)			Not supported
		Zone data visualisation format is very similar to the 'Output for Zone/Hazard Sub-Volumes', but has n (default 10) layers, each with a value. It has the same zone layout as a hazard zone but has more refinement in the height direction rather than being limited to crawling and walking head height. This approach is sufficiently flexible to allow some alternate post-processing.			
		Cut Plane settings [Plane orientation, Number of Planes, Space, X Y Z Position, Threshold] and the field variable selection			
		Monitor Line settings [Name, Direction of line, X-axis variable (Plot 1), Y-axis variable (Plot 1), X-axis variable (Plot 2), Y-axis variable (Plot 2), X-axis variable (Plot 3), Y-axis variable (Plot 3)] and the field variable selection			
		Monitor Cell settings [Name, Use as FED probe, FED RMV, FED PID, FED DR (pain),			

Data category	Data subcategory	Attribute/Property	Data type	Range of values	Support in BIM IFC Model
		FED DR (incapacitation)] and the field variable selection			
		Other Common Export Formats			Not supported
		The simulation data can be exported in several other common formats			
Time to flashover		Not a direct output. However, time to flashover can be found by analysing values of other output variables.			Not supported
Output of sprinkler and fire detector activation time		The times and activating conditions for detectors or sprinklers as a confirmation check that correct behaviour and activation were predicted.			Not supported

B5 FSE based analysis preliminary database - list of tables and fields

In Table B5, the FSE based analysis preliminary database is presented along with a list of tables and their fields. This database is mainly FSE output data focussed and covers a subset of the level of information presented in Subsection B3 and Subsection B4.

It should be noted that an additional table labelled ‘BuildingProjectInfoTbl’ (not included here), with ‘one to many’ relationship with the ‘ScenarioTbl’, was added to the database to mainly store ID references to some BIMserver items (Project ID, Project Revision ID, and a number of IDs related to the extended data). Also, in the same table i.e. BuildingProjectInfoTbl, other fields of general nature were added as well. These fields include the following information: Name of the tool used for evacuation modelling, name of the tool used for fire modelling, brief analysis conclusion, and analysis outcome report file that can be attached to the database.

Table B5: FSE based analysis preliminary database

Table	Field	Data type	Brief description
Scenario	ScenarioID	Number	Primary key
	ScenarioName	Text	Name of the fire/evacuation scenario
	ScenarioDescription	Text	A brief description of the scenario
	AssumptionsMade	Text	Assumptions made about the scenario
	ASETValue	Number	The ASET value calculated for the scenario
	RSETValue	Number	The RSET value calculated for the scenario
	BriefStatementOfOutcome	Text	Brief description of the analysis outcome for the scenario
FireEvacZone	FireEvacZoneID	Number	Primary Key
	FireEvacZoneName	Text	Name of the fire/evacuation zone
	ScenarioID	Number	Foreign key
Level	LevelID	Number	Primary Key
	Level	Text	Level name
	Floor	Text	Floor name
Exit	ExitID	Number	Primary Key
	ExitName	Text	Exit label
	ExitDescription	Text	Description of the exit
	FlowRate	Number	Unit flow rate
	Usage type	Text	Exit usage type

Table	Field	Data type	Brief description
	Potential	Number	A higher value for potential means less attractive the exit becomes because the occupants head for positions of lower potential
	Attractiveness	Number	Probability of occupant's awareness of the existence of this exit
EvacuationSimulation	EvacSimulationID	Number	Primary Key
	EvacSimStartTime	Number	Simulation start time
	EvacSimEndTime	Number	Simulation end time
	TotalNumOfSimPeople	Number	Total number of simulated agents (occupants)
	NumOfMales	Number	Number of male agents
	NumOfFemales	Number	Number of female agents
	NumOfPeopleOut	Number	Total number of agents evacuated
	FirstPersonOutTime	Number	Time the first agent evacuated
	LastPersonOutTime	Number	Time the last agent evacuated
	NumOfFatalities	Number	Number of fatalities (in case of coupled fire/evacuation analysis)
	FirstFatalityTime	Number	Time of first fatality (for coupled analysis)
	LastFatalityTime	Number	Time of last fatality (for coupled fire/evacuation analysis)
	EvacSimulationFile	Attachment	Simulation file generated by the evacuation modelling tool added as an attachment
	ScenarioID	Number	Foreign key
SimulatedOccupant	SimOccupantID	Number	Primary Key
	SimOccupantPosInSim	Number	ID/Number assigned to the Agent (simulated occupant) by the evacuation modelling tool
	Gender	Text	Agent's gender
	Age	Number	Agent's age
	Weight	Number	Agent's weight
	StartNode	Text	Agent's starting location (Node label)
	EndNode	Text	Agent's last location (Node label)
	DistanceTravelled	Number	Distance travelled by the agent
	ResponseTime	Number	Agent's response time
	Mobility	Number	Agent's level of mobility
	CumulativeWaitingTime	Number	Agent's cumulative waiting time
	PersonalElapsedTime	Number	Agent's personal elapsed time
	FIH	Number	FIH measures the occupant’s combined cumulative exposure to convective and radiative heat.
	FICO2	Number	FICO2 measures occupant’s cumulative exposure to carbon dioxide gas (CO2).

Table	Field	Data type	Brief description
	FIN	Number	Reflects the level of incapacitation due to narcotic gases
	Awareness	Text	Agent's environment awareness
	Patience	Text	Agent's patience level
	WalkSpeed	Number	Agent's walking speed
	LevelID	Number	Foreign key
	EvacSimulationID	Number	Foreign key
	ExitUsedID	Number	Foreign key
EvacSimLevelPerformance	NumberStarted	Number	Number of agents started on this level
	LastExitTime	Number	Level's last agent exit time
	LevelID	Number	Foreign key
	EvacSimulationID	Number	Foreign key
EvacSimExitPerformance	TotalNumberUsedIt	Number	Number of agents used this exit
	FirstOutTime	Number	Time of the first agent to use this exit
	LastOutTime	Number	Time of the last agent to use this exit
	ExitID	Number	Foreign key
	EvacSimulationID	Number	Foreign key
FireSimulation	FireSimulationID	Number	Primary key
	FireSimStartTime	Number	Fire simulation start time
	FireSimEndTime	Number	Fire simulation end time
	FireSize	Number	Fire size
	FireGrowthType	Number	Fire growth type
	FireSimulationFile	Attachment	Simulation file generated by the fire modelling tool added as an attachment
	ScenarioID	Number	Foreign key
FireSimZoneHazard	UpperValue	Number	Upper layer value for the hazard
	LowerValue	Number	Lower layer value for the hazard
	TimeInterval	Number	Time the hazard values were taken
	FireSimID	Number	Foreign key
	HazardTypeID	Number	Foreign key
	FireEvacZoneID	Number	Foreign key
HazardType	HazardTypeID	Number	Primary key
	HazardTypeName	Text	Hazard type (e.g. temp, smoke, CO).
	HazardTypeDescription	Text	Hazard description

APPENDIX C: FSE Extended Data Schema for BIMserver

The Extended Data Schema named 'FIRE_EVAC_SIM_DATA_JSON' has application/json as its content-type and it was created for FSE based analysis data requests for BIMserver. The JSON structure (without data) used for various types of requests for the prototype system for testing data sharing between BIM and FSE is shown below:

Fire Safety Engineering based analysis request - Initial response (JSON)

Note: This file captures basic information such as analysis request and initial response.

```
[
  {
    reqFor: "",
    reqResponseMsg: ""
  }
]
```

Fire Safety Engineering based analysis request - Final response (JSON)

Note: This file captures basic information such as analysis request and final response. The structure of initial and final response files is the same.

```
[
  {
    reqFor: "",
```

reqResponseMsg: "”
}
]

Fire Safety Engineering based analysis data - list of available queries (JSON)

Note: This file captures information about the available queries that can be executed by a client.

[
{
id: "",
name: "",
displayName: ""
},
{
id: "",
name: "",
displayName: ""
}
]

Fire Safety Engineering based analysis data - All queries output (JSON)

Note: This file captures the output of all queries.


```
[
  {
    displayName: "",
    fieldName: "",
    fieldDataType: "",
    fieldValue: ""
  },
  {
    displayName: "",
    fieldName: "",
    fieldDataType: "",
    fieldValue: “”
  },
]
```