Journal Pre-proof

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PII: S2352-7102(21)00652-5

DOI: https://doi.org/10.1016/j.jobe.2021.102794

Reference: JOBE 102794

To appear in: *Journal of Building Engineering*

Received Date: 25 December 2020

Revised Date: 10 May 2021

Accepted Date: 26 May 2021

CRediT authorship contribution statement

Asim A Siddiqui: Conceptualization, Methodology, Investigation, Software, Writing - original draft, Writing - review & editing. **John A Ewer:** Conceptualization, Supervision, Methodology, Writing - review & editing. **Peter J Lawrence:** Conceptualization, Supervision, Methodology, Writing - review & editing. **Edwin R Galea:** Conceptualization, Supervision, Methodology, Writing - review & editing. **Ian R Frost:** Software.

Building Information Modelling for performance-based Fire Safety Engineering analysis – a strategy for data sharing

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Abstract

The Hackitt Report into the tragic loss of 72 lives in the Grenfell Tower fire, identified failures and poor practices associated with the UK construction industry. To address these failures the report makes several recommendations, including the development of a "golden thread of information" to be embedded throughout the entire building lifecycle enabling the recording and preservation of information. This is to be achieved through Building Information Modelling (BIM). However, to create a "golden thread of information" in BIM from the Fire Safety Engineering (FSE) perspective particularly for the performance-based approach, many significant challenges and limitations must be resolved. These challenges include the fact that no FSE specific information exchange is available in BIM and that the results produced by fire and evacuation modelling tools are not explicitly captured in the BIM Industry Foundation Classes (IFC) Model. Of the FSE tools that support BIM, this is mainly limited to geometry extraction from an IFC file. In this paper, a practical conceptual strategy to pave the way to resolve these problems is proposed. A number of developments by the authors are discussed, forming part of an international collaboration project proposal administered by buildingSMART to enhance the IFC Model from the FSE perspective. Additionally, to evaluate and demonstrate the benefits of two-way data flow between BIM and FSE tools, a prototype system together with a preliminary FSE based analysis database have been developed. The work presented in this paper, provides a practical road map for creating a 'golden thread of information' in BIM for performance-based FSE analysis.

Keywords

Building Information Modelling; Fire Safety Engineering; Evacuation Modelling; Fire Modelling; Industry Foundation Classes;

1. Introduction

In response to the tragic Grenfell Tower fire [1], in which 72 people lost their lives, the UK Government commissioned an independent review (Hackitt Report [2]) of UK building regulations and fire safety practices. The significance of the Hackitt report is that it not only provides an understanding of the contributory causes of the Grenfell tragedy, but also identifies deep, pervasive flaws in the culture and practice of the UK construction industry and fire safety sector. Without concerted action to address these failings, the industry risks further tragic loss of life, and significant additional time and cost burdens arising during design and construction [3], through life maintenance and the modification of buildings for change of use.

The report highlighted the critical need to improve the quality of construction and thereby the associated life safety performance of buildings. Associated with this, it identified the importance of embedding a "golden thread of information" within the full lifecycle of the building, ensuring the storage and easy accessibility of all information relating to the building design, its construction and through life maintenance i.e., storing of information detailing how the building was designed, built, and maintained (full lifecycle information) [4].

This critical need was demonstrated by the many months it took, post Grenfell, even to simply identify the materials used in façade construction in high-rise residential buildings throughout the UK. One way to achieve the golden thread recommended in the Hackett Report is through the use of digital techniques offered by Building Information Modelling (BIM). BIM enables the recording and preservation of information throughout the building lifecycle.

Various governments around the world, including the UK Government [5], strongly support the adoption of BIM within the Architecture, Engineering and Construction (AEC) industry. A survey of BIM uptake in UK architectural offices [6] has highlighted perceived initial investment and staff training cost, lack of understanding of BIM's capabilities, and perception that BIM is too sophisticated are the main factors slowing down BIM adoption. Despite these challenges, BIM has been increasingly embraced by various disciplines within the AEC industry, particularly the architecture discipline [7], but its adoption within the engineering disciplines is still not high. A recent survey by the Institute of Civil Engineers and ALLPLAN UK (a European vendor of open solutions for BIM) [8] has reported incomplete design data from other disciplines to be the biggest source of errors on projects. This along with the risk of introduction of errors due to design changes, incompatible software, and exchanging information between disciplines and software systems, is a source of frustration even for those engineers already utilising aspects of BIM on projects. The fire safety sector within the industry is slow in embracing digital technology [9], and within the engineering disciplines, the authors believe Fire Safety Engineering (FSE) lags far behind its peers in BIM adoption. This is supported by the findings of a recent online Survey of Pedestrian Evacuation Models [10]. The survey found that BIM tools were used by only 21% of respondents for evacuation modelling while 12% did not even know what BIM meant. Interestingly, 55% of respondents would like to see further integration with BIM to save time (such as automatic geometry building functionality).

The authors suggest that a key reason for this slow uptake of BIM by the FSE community, is the current inability of the BIM "golden thread of information" to deliver the functionality and capabilities required by data hungry FSE tools, and assimilate and store their data rich outputs. The authors further suggest that this is because FSE does not have its own domain specific sub-model, equivalent to the architectural model and structural model, which cater to the specific needs of the architectural and structural engineering disciplines, respectively. While this situation has been inherited by BIM, rather than persisting with it, serious consideration should be given to an FSE-based fire safety analysis sub-model. This would allow key building fire safety information, such as exit routes, congestion areas, and exit usage, to be shared with stakeholders in a more informed, coherent, and efficient manner.

As already identified, while there are broader issues impacting the uptake of BIM within the various engineering disciplines, the focus of this paper is to investigate how effective data sharing can be achieved between BIM and fire and evacuation modelling tools used for performance-based FSE analysis.

Based on a review by the authors of BIM Industry Foundation Classes (IFC) and the requirements of fire and evacuation modelling tools, the following key challenges and limitations must be addressed by BIM to facilitate a productive workflow for performance-based FSE analysis while simultaneously addressing the requirements for the "golden thread of fire safety information":

- Within the BIM Industry Foundation Classes (IFC) Model, the input data requirements for FSE are not fully supported and significantly, there is currently no FSE specific filtered view of the data, making data extraction and manipulation difficult.
- The key output data generated by the fire and evacuation modelling tools as part of fire safety analysis is not explicitly captured or supported in the IFC Model. Related to this, information such as which software and version was used, how it was used, what modelling assumptions were made and the assessments of how the results demonstrated, is also not explicitly captured in the IFC Model.
- Only a few fire and evacuation modelling tools have geometry extraction support for BIM based data and their outputs do not directly feed back into BIM to share with other disciplines or to preserve the critical FSE information alongside the building design.
- No BIM based building design tool has data export facilitates that are intended for specific consumption by fire and evacuation modelling tools.

To begin addressing the highlighted limitations in BIM, for performance-based FSE analysis, this paper proposes a practical conceptual strategy to demonstrate data sharing between BIM and several FSE modelling tools. The strategy provides a road map for addressing the current limitations whilst supporting a framework for the future direction of BIM development with integrated FSE. Part of this strategy is enhancement and extension of the current BIM IFC Model, and to realise the required enhancements, an international collaboration project in association with BIM Standards Organisation buildingSMART has been initiated. The initial research undertaken by the authors, in support of this strategy, includes the initial analysis of information exchange requirements for FSE within the BIM context, the implementation of BIM data import capabilities in exemplar fire and evacuation modelling tools, SMARTFIRE [11] and buildingEXODUS [12], and a prototype system for evaluating two-way data sharing between BIM and FSE, which includes a preliminary database design capable of capturing fire and evacuation modelling generated simulation data.

While the effort required to deliver the strategy is significant, a seamless integration of FSE within BIM offers substantial benefits to all key stakeholders within the AEC industry. These include faster and more reliable process of data acquiring and sharing, full audit trail, relatively quicker post-fire incident analysis, improved management of change (e.g. refurbishment resulting in usage/occupancy changes and temporary changes for events) as well as improved incident management due to helping to ensure that the information in BIM is "as built". Furthermore, this can lead to the use of Digital Twin Technology, a virtual representation of a physical asset with a focus on its performance and behaviour under certain conditions of interest. This capability also has an important role in future Smart Buildings technology i.e. buildings that use automated systems to control the building operation to achieve required levels of efficiency, comfort, and safety. For example, one potential application is the development of an intelligent active dynamic evacuation management system facilitated by the data provided by BIM, sensor data providing instantaneous information concerning the location of the population, sensor data providing information relating to the developing fire, a network of dynamic signs [13], along with faster-than-real-time evacuation simulation [14]. Such a combination of technologies can be used to identify near optimal evacuation routes for the at-risk population and guide them to safe exits in response to an evolving emergency incident.

Improving the support for FSE within BIM also facilitates other aspects of building design, which are currently not fully catered for, such as pedestrian dynamics analysis and analyses related to other types of hazards such as airborne pathogens. One prominent and critical recent example of this is provided by the COVID-19 pandemic [15]. The need for physical distancing and effective ventilation as means for managing infection risk has highlighted other aspects of building design safety analysis and facility management for which suitably adapted FSE simulation tools can provide an essential capability to assess building layout and operating procedures. For example, Computational Fluid Dynamics (CFD) based fire modelling tools with droplet modelling capabilities are being used to simulate the dispersal of Sars-Cov-2 viral aerosols and their interaction with ventilation systems; while agent based evacuation models are being used to simulate and assess the impact of physical distancing requirements on the operation of infrastructure [16]. The data and modelling requirements, for these emerging building safety applications, are very similar to the requirements of FSE applications and so will also benefit from many of the BIM enhancements proposed in this paper.

The key challenges in BIM for FSE are covered in more detail in Section 2 after introducing some essential aspects of BIM and FSE. Section 3 details the conceptual strategy and the development work in its support by the authors, to address these challenges. Section 4 describes a prototype system that was used to evaluate two-way data sharing between BIM and FSE. Section 5 contains a summary discussion of the issues raised in this paper, and finally, Section 6 indicates conclusions and the direction for future work.

2. BIM with FSE data sharing

2.1 BIM

The use of digital technology has been around for decades, particularly in the Aerospace and Automotive industries, and has provided data management through the digital representation of a physical asset. In contrast, the use of digital technology is a comparatively new concept for the AEC industry which has suffered from various data sharing problems, such as those related to software interoperability, version control, information accuracy, projects routinely exceeding schedule/budget, as well as legal claims and litigation [17]. In the mid-1990s, initial developments in the AEC industry began to address these problems in an attempt to realise potential benefits offered by digital technology, with the term Building Information Modelling (BIM) being introduced in 2002. BIM is also called Building Information Model i.e. the model produced by applying the modelling process and even Building Information Management [18]. The BIM based data exchange then became a standard in 2013 [19], which was further revised in 2018 [20].

BIM is a process of creating a virtual building model by defining a building as a combination of objects and information. The objects exist in a database with parameters and relations to other objects that allow conflicts and design problems to be detected. While the background to the introduction of BIM has been covered elsewhere [21], it is worth noting that this approach represents a major change for the AEC industry. While the AEC industry has made heavy use of Computer-Aided Design (CAD) for many years there are many serious limitations to this technology, including: misuse of layers and bad scaling that can lead to inappropriate objects such as: wiring being interpreted as geometry resulting in errors in the interpretation of the geometry, the building as-built may not match the plans, no clash detection, often highly complex with multiple layers, often only 2D resulting in missing height information for doors/windows/ceilings/etc., no filtering of unnecessary details, as well as version compatibility issues. The motivation behind BIM is to address these problems by providing a collaborative and information rich approach to facilitate data sharing between various disciplines and applications throughout the lifecycle of a building.

OpenBIM is an initiative of buildingSMART (an open, neutral and international not-for-profit organisation) with support from several leading software vendors, that has developed an open data model called IFC to resolve data sharing and interoperability problems. IFC represents an open specification for BIM data that is exchanged and shared among the various collaborators within a building project [19]. The data schema architecture of IFC defines four conceptual layers (Resource, Core, Interoperability, and Domain) that contain several schemas for capturing and sharing of not only general, but also discipline specific building data. The current major version is IFC4 which was released in 2013 [22] and registered as the ISO 16739:2013 Standard [19]. Through several addendums and a technical corrigendum, it was then revised as the ISO 16739-1:2018 Standard [20]. Since then, further updates have been made to IFC4, and at the time of writing, the latest update IFC4.3 RC2 was published in November 2020, which has support for new domains such as Ports and Waterways, Rail, Road, and Tunnels [23].

A roadmap of BIM evolution, which maps the beginnings of BIM and sets out the goals for its future development, is represented using the BIM Evolution/Maturity diagram created by Bew and Richards in 2008. This diagram captures the evolution from CAD to early BIM concepts and charts out its progressive development through four incremental capability levels; Level 0 (no collaboration and only 2D CAD), Level 1 (a combination of 3D and 2D CAD is utilised), Level 2 (by using a common file format there is a collaboration between the stakeholders who use their own 3D CAD models), and Level 3 (a fully integrated single shared BIM model held in a centralised repository, which preferably facilitates communication through a cloud-based web services solution). Currently, the AEC industry is generally acknowledged to be moving towards Level 2.

The UK Government's Construction 2025 vision [5] 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, more quickly and more efficiently, the implementation of BIM will be necessary. The UK government has produced a series of key documents and standards covering various aspects of BIM for the industry. For instance, the PAS1192 series which provided solid foundation and led to the development of ISO 19650 series of international standards [24]. As previously mentioned, the Hackitt Report [2] made several recommendations including a need for a "golden thread of information" to be embedded throughout the entire building lifecycle. Based on the Hackitt Report recommendations, the UK Government set out an intention to develop a new regulatory framework in a consultation document in 2019. The response to this consultation by the UK Government was then published in 2020 [25] and a new bill introduced, the 'Fire Safety Bill 2019-2020' to improve fire safety in buildings in England and Wales [26]. More legislation is expected to follow that will further support the aims of BIM, such as improved data clarity by maintaining a digital audit trail. Also, related to this, the British Standards Institute (BSI) is currently working on a new standard on the Digital Management of Fire Safety Information called BS 8644 [27]. Despite various challenges [9, 28], these are positive developments.

The EU has also been active in encouraging the development of BIM. In 2016, the EU BIM Task Group, a network supported by the European Commission, was founded. In 2017, they produced a handbook identifying their strategy for the introduction of BIM by the European Public Sector [29].

The support for BIM in various countries around the world has been reported [30, 31, 32, 33, 34, 35, 36]. For instance, in the United States, some states have put BIM mandates in place, in Germany, BIM will be required for new transportation projects from the end of 2020 [37], Scandinavian countries are the early adopters of BIM and have public standards currently in place, and BIM is also mandated in France.

2.2 FSE

Fire Safety Engineering (FSE), a safety support discipline, plays a central role in the building lifecycle as it enables engineers to analyse the fire safety aspects of a building by applying scientific and engineering principles [38]. This is essential during the design phase, but also in the event of through-life modifications to the building, changes in building usage, facility management and for forensic analysis of fire incidents. FSE makes use of a range of fire and evacuation modelling tools, requiring a wide variety of building specific data, including building geometry, physical properties of materials used in construction, nature of the proposed occupancy, number of proposed occupants, evacuation routes, types of alarm, proposed fire and smoke management systems. Moreover, the fire and evacuation analyses results, produced by these tools, are communicated with architects and designers so that the design can either be approved or improved as appropriate [39].

Within FSE, the key fire safety objectives include safety of life, property protection, continuity of operations, protection of the environment, and preservation of heritage [40]. To ensure these objectives are met, two fire safety design methods are commonly used. The first is the traditional Prescriptive Method which uses a set of rules to determine the egress design and the required level of fire protection. The second, more recent approach is the Performance-Based Approach (PBA), which applies an engineering approach to achieve fire safety objectives by focusing on key “performance” metrics (determined through simulation for the specific building design, proposed occupant distribution, and challenge scenarios), such as the required time for evacuation and the available time for safe evacuation [41].

The PBA to FSE is a relatively recent but evolving safety support discipline which requires 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 makes the PBA and FSE not only complex but also highly intercoupled with other domains.

By utilising modelling and simulations, a common approach to performance-based FSE analysis is to determine, for a given scenario or scenarios, if the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET) plus a suitable safety margin. The ASET is driven by the fire development and determined by a fire simulation, while RSET is driven by human behaviour and often determined by an evacuation simulation. For a given scenario, the RSET is commonly defined as the time required to complete the evacuation, while the ASET is commonly determined by the time required for fire parameters, such as temperature, radiative flux, smoke concentration or toxic gas concentration at head height, at key locations within the geometry to reach identified critical life safety conditions (tenability limits – as stipulated/required by guidelines/regulations). The safety margin is a multiplicative or additive adjustment applied to the calculated RSET to compensate for uncertainty in methods, calculations, input data and assumptions [40] (see Fig 1 for details). It should be noted that another approach is to use coupled fire and evacuation analysis, where the impact of fire hazards on the population is directly taken into consideration during the evacuation simulation and so RSET and ASET values are not explicitly determined. Although this approach is less common, it can provide more realistic results [42]. In the RSET and ASET approach, the evacuation analysis is undertaken without exposing the population to the evolving fire atmosphere, and so the fire does not impact the evacuation dynamics in any way. In the coupled approach, the evacuating population are exposed to the developing fire hazards which may have an impact on their performance or the decisions they make during the evacuation. Using such an analysis, it is possible to derive a more realistic estimation of evacuation times and to determine the impact of the cumulative exposure of evacuees to fire hazards i.e. number of expected fatalities and injury levels.

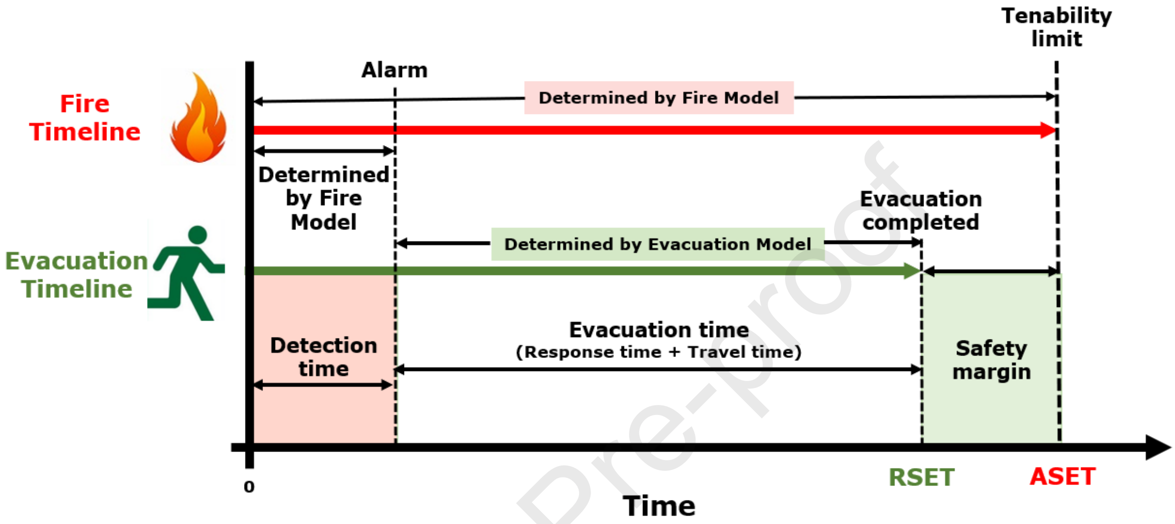


Fig. 1. ASET and RSET analysis

2.3 BIM - FSE data sharing

In the evolutionary development of BIM, the current AEC industry is generally acknowledged to be moving towards Level 2, where interdisciplinary collaboration is the goal. For instance, the UK Government's BIM mandate has significantly increased awareness and adoption of BIM in the UK [7] but from the FSE perspective, it is not necessarily fully fit for purpose. Furthermore, the goal is to reach BIM Level 3 which focusses on integration, but this will require active participation and contribution from various disciplines and BIM vendors. Reaching this desired level of BIM development is likely to take several more years with developments such as the IFC file format being a positive contribution to achieving this goal.

Data sharing between BIM and FSE tools sets (fire and evacuation modelling tools) is at an earlier stage of development. Even though some level of support exists within BIM for required FSE input data, there is no explicit provision for the fire and evacuation modelling generated safety analysis output data. However, it is important to acknowledge that despite this lack of explicit support, some BIM packages such as Autodesk Revit [43] do provide options to add custom data-sets to any element. Nevertheless, the explicit support in the IFC Model is essential to provide a consistent approach across BIM packages that is not limited to a specific project. In contrast, based on a review by the authors, the support for BIM data in fire and evacuation modelling tools is very limited and is restricted to building geometry extraction from IFC files by only a small number of FSE modelling tools. Also, even the geometry that is available is rarely fully compatible with FSE modelling tools, having either unnecessary details or inconsistencies that prevent direct usage for modelling.

Anecdotally, many FSE practitioners are required to adapt and clean up their CAD model in order to obtain suitable IFC data for FSE modelling. Support for the input data requirements for various fire and evacuation modelling tools, are either poorly- or un- defined or required data is fragmented within the BIM context. Furthermore, the nature and type of simulation outputs, produced by these modelling tools, vary hugely between similar types/classes of software from different vendors, but have no supporting broad definition within BIM. This is the main reason that FSE needs to have its own domain specific sub-model, equivalent to the BIM architectural model or structural model, which will cater for the specific needs of FSE.

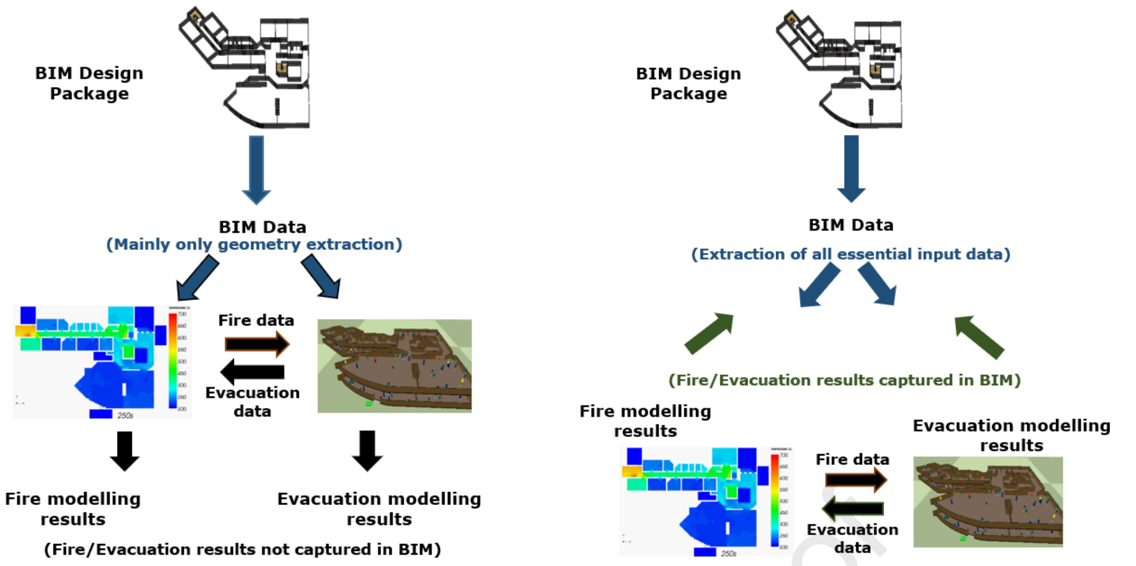
There have been several research studies exploring some aspect of fire safety interaction with BIM. Earlier work includes BIM IFC v2x2 data extraction from an IFC file between a CAD program and the BRANZFIRE fire modelling tool by [44] and the development of a conversion tool for Computational Fluid Dynamics (CFD) based fire modelling tool Fire Dynamics Simulator (FDS) in combination with a revised version of Fire Engineering IFC Model parser [45]. Other examples include: the development of 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 [46]; the development of a pedestrian simulation tool to work with BIM IFC geometry data import [47]; a process of exchanging BIM and Regulatory Knowledge Model data with a risk-based fire evacuation simulation tool EvacuatioNZ [48]; and a comparison of two comparative approaches to provide data from an IFC file as input for the FDS fire modelling tool [49].

These examples provide valuable insights into BIM with fire safety related data sharing aspects. However, to achieve full benefits of BIM for FSE a collaborative effort from stakeholders is needed. To support this, a conceptual strategy is proposed in Section 3, which is needed to cater for various aspects of BIM with enhancements to the IFC Model from the FSE perspective.

3. A strategy for data sharing between performance-based FSE analysis and BIM

The focus of this paper is to address the key challenges associated with data sharing between BIM IFC Model and fire and evacuation modelling tools.

The lack of support for capturing and sharing simulation results in the current BIM IFC Model means there is essentially only a one-way data flow (see Fig. 2a). Enhanced two-way data sharing between FSE and BIM is required, to not only fully address the problems associated with the CAD based approach but also to overcome the limitations of the current BIM, including adding the capability to capture the fire and evacuation simulation data (see Fig. 2b).



(a) Current BIM with performance-based FSE (b) Enhanced BIM with performance-based FSE

Fig. 2. Current and enhanced BIM with performance-based FSE

Before presenting the conceptual strategy to address these limitations, it is essential to mention two important concepts in BIM which have direct relevance to the strategy. The first is the Model View Definition (MVD), which for an information exchange provides a technical description as a subset of the IFC schema [50]. The buildingSMART developed officially released or under development MVDs are listed on their website [51]. In addition to the official MVDs, additional MVDs are under development by organisations or teams that are not part of buildingSMART International. The second concept is called Information Delivery Manual (IDM) which is focussed on not only capturing but also specifying processes and flow of information [52]. The requirements are defined in an IDM and are translated into an MVD. Related to this, it is worth mentioning a buildingSMART project called Information Delivery Specification (IDS) which is currently in progress, to define machine readable data exchange requirements based on industry standard technologies for improved data exchange workflows [53].

3.1 Strategy overview

The proposed strategy, developed as part of a doctoral research project [54], is one approach to address the identified key challenges. Furthermore, the proposed strategy also addresses the broader issues related to incomplete or missing data within the FSE context. Where other sources are used as part of the development of the proposed strategy, these have been acknowledged.

The proposed strategy for enhanced BIM integration with performance-based FSE comprises three development steps are described in detail below:

Step 1: Enhance IFC Model Specification for FSE

It is essential that the IFC Model is enhanced to provide a FSE specific view of the building by supporting the required input data as well as the key output data. Furthermore, it is important that this shared fire related data uses a software independent format [55]. Therefore, the first step is to not only identify the required input and output data but also provide a means to represent it in the IFC Model. To initiate this process, the authors, who are experienced users and developers of fire and evacuation modelling tools, have assembled initial data requirements for performance-based FSE analysis to work with BIM (see Section 3.2). This initial analysis will contribute to the data gathering phase of the international collaboration project with BIM Standards organisation buildingSMART. This collaborative effort involving multinational fire safety professionals is essential to ensure that the future IFC Specification has the support of the broad FSE community and supports the needs of FSE practice. The MVD for FSE will involve the following three key aspects:

a) Identify Input data required by fire and evacuation modelling tools for fire safety analysis: Based on the review by the authors, it was found that the current IFC Specification (IFC4) does not fully support the input data required by fire and evacuation modelling tools (see Supplementary material Table S1). To develop an FSE specific view of the data, it is essential this support is formally evaluated, and required changes and additions identified. As suggested above, this can be achieved through a buildingSMART administered international collaboration project.

b) Identify key output data from fire and evacuation modelling tools: Based on the review by the authors, it was found that the FSE output data generated by fire and evacuation modelling tools is not captured by the current IFC Specification. This data is needed to facilitate the stakeholders to not only acquire an improved understanding of the design phase FSE based analysis results, but also to support the making of more informed decisions concerning potential future changes to building design and usage.

c) Capture the identified input/output data in the IFC Model Specification: The input elements and properties identified in (a) will be compared with the current IFC Specification. This will assist in finding out which specific identified FSE input elements and properties are not already supported in the IFC Specification. Based on that, specific additions to the IFC Model can be made. For the identified key output data identified in (b), new entities and properties will be defined and incorporated within the IFC Specification. As with (a) and (b), (c) will be an essential component of the collaboration project with buildingSMART.

The outcome of Step 1 will be the development of an IDM which is translated into an MVD for FSE as part of an international collaboration project in accordance with buildingSMART procedure.

Step 2: Implement enhanced IFC Model Specification

On completion of Step 1, the enhanced IFC specification will be produced which will then require implementation support in various BIM design tools. This support will include an export option in the BIM design tools for the FSE MVD. Various widely used BIM design tools support existing MVDs, for example:

- Revit IFC export option supports several versions of IFC and model views, for instance, IFC 2x3 Coordination View, IFC2x3 Basic FM Handover View, and IFC4 Design Transfer View [56].
- Vectorworks IFC export option supports several versions of IFC and model views, for instance, IFC 2x3 Coordination View, and IFC4 Reference View [57].
- ARCHICAD IFC export option supports several versions of IFC and model views, for instance, IFC2x3 Coordination View, IFC4 Reference View, and IFC4 Design Transfer View [58].

It is important to highlight 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 BIM design tools (e.g. Revit) to provide support for a certain level of FSE relevant data. However, what is required is explicit support, in the IFC Specification, for all the FSE required elements and properties. With the development of an explicit IFC Model Specification and FSE specific MVD, BIM design tools will be able to provide support which is not ad hoc or limited to one BIM package for use only on a single project. The outcome of this step will be a standard approach to data extraction and sharing, from the FSE perspective.

Step 3: Enhance fire and evacuation modelling tools to support BIM

In addition to enhancing the capabilities of BIM to support FSE, fire and evacuation modelling tools used for performance-based FSE analysis need to be enhanced to support BIM. This development will require two key enhancements:

a) Add/enhance the capability to import BIM data for input in fire and evacuation modelling tools for FSE based analysis: Based on a review by the authors (see for example [54]), many fire and evacuation modelling tools currently do not support the import of data from an IFC file. Even those tools which have provided support for IFC, typically have their capabilities limited primarily to basic building geometry extraction. To support the existing IFC Model, fire and evacuation tools should either add IFC data import capability or significantly enhance the existing capabilities. To support the future enhanced IFC Model, completion of Step 1 and Step 2 is required. This is discussed further in Section 3.2.

b) Add capability to export key output data generated by fire and evacuation modelling tools as part of FSE based analysis to BIM: This development work depends on the inclusion of fire safety analysis output data in the next version of IFC Specification and its implementation support in various BIM design tools such as Revit and Vectorworks. Moreover, the fire and evacuation modelling tools use various file formats to export output data, which are often proprietary. A suitable data export capability in support for BIM will be required.

The conceptual strategy to achieve enhanced BIM with FSE data sharing (see Fig. 2b), is summarised in Table 1.

Table 1. Enhanced BIM with FSE data sharing conceptual strategy

Step	**Key activities**

Step 1: Enhance IFC Model Specification for FSE	Authors to gather initial list of input and output data requirements for fire and evacuation modelling tools to work with BIM. As part of an international collaboration project with buildingSMART, develop an MVD for FSE data exchange. The above mentioned work by the authors will be used in this project. 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. c) Capture the identified input/output data in the IFC Model Specification.
Step 2: Implement enhanced IFC Model Specification	After adoption of the proposed changes to IFC Specification, the BIM design tool developers will be expected to provide implementation support for it.
Step 3: Enhance fire and evacuation modelling tools to provide support for BIM	a) Add/enhance the capability to import BIM data for input in fire and evacuation modelling tools for FSE based analysis. b) Add the capability to export key output data generated by fire and evacuation modelling tools as part of FSE based analysis to BIM.

3.2 Progress and development in support of the Strategy

The authors progressed the conceptual strategy with contributions to the first and third steps of the strategy. These developments have involved initial data gathering of data requirements for performance-based FSE analysis by the authors and also collaboration with international partners for an MVD for FSE project administered by buildingSMART [59] as part of Step 1. In addition, the authors have made progress with Step 3 by exploring BIM data exchange capabilities for the evacuation modelling tool buildingEXODUS [12] and the CFD fire modelling tool SMARTFIRE [11]. Developments for Step 2 have been limited as this requires the input from vendors of BIM design tools. These development efforts are summarised in Fig. 3 followed by further description.

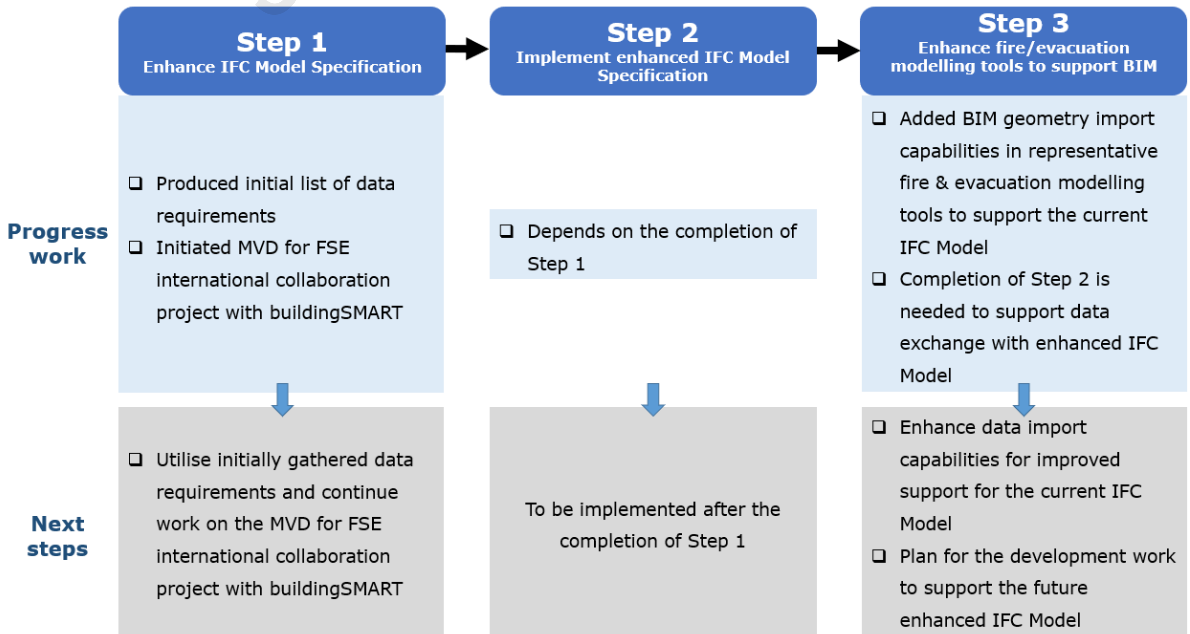


Fig. 3. Development efforts in support of the strategy

Progress in work to support Step 1 - Enhance IFC Model Specification

As part of this work, the authors have assembled data requirements for performance-based FSE analysis which provides an initial contribution to the data gathering phase of the international collaboration project administered by buildingSMART. The British Standards framework BS 7974, which describes a basic framework for the application of FSE [38], was used as an initial guide for this work. BS 7974 is supported by a series of published documents that provide additional guidance on FSE. The sub-system 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 [60], was loosely used for guidance. However, it should be noted that the collaboration project will support multiple standards.

Based on this initial analysis, the broad input data categories required for fire and evacuation modelling, to aid in fire safety analysis and the level of support for them in BIM, is shown in Supplementary material Table S1. Similarly, Table S2 in Supplementary material provides information concerning the broad data output from fire and evacuation modelling tools as part of the fire safety analysis. Based on these broad categories of input and output data, a full list of data properties, including their range of values in evacuation modelling tool buildingEXODUS, has been produced, though this is not included in this paper due to space limitations. Furthermore, work is in progress to produce a full list of data properties, including their range of values, for the following three evacuation modelling tools: MassMotion [61], STEPS [62] and Pathfinder [63]. Similarly, based on the broad categories of input and output data in Supplementary material Table S1 and Table S2, a full list of data properties in fire modelling tool SMARTFIRE has been produced, but have not been included in this paper for the same reason. Furthermore, work is progressing to produce a full list of data properties, including their range of values, for another fire modelling tool PyroSim [64]. It should be noted that these tools are broadly representative examples of fire and evacuation modelling tools, and also have some support for BIM IFC file import. Once the analysis has furnished a broadly defined and representative set of input and output data from the investigated FSE software, it will be necessary to abstract these data requirements in an attempt to provide software independent support for arbitrary FSE tools.

This work will contribute to the international collaboration project, administered by buildingSMART, which the authors, along with a team of international project partners, have initiated to develop support in the IFC Model for FSE and also non-emergency movement of people [59]. Even though this paper is focussed on performance-based FSE analysis, the scope of the collaboration project is wider as it includes the non-emergency movement of people. This type of analysis, while not directly related to FSE, is an important consideration in building design as it defines the pedestrian dynamics associated with the normal use of the building. The information can also be useful to FSE to define starting locations and population densities in the event of a fire or emergency incident. The development work, as part of the above-mentioned international collaborative project within buildingSMART, will lead to the development of an MVD for FSE, and also for non-emergency movement of people. Part of this development will be outreach and promotion of the project and its potential benefits using a suitable set of use cases.

How the currently unsupported FSE required data in the IFC Model will be added in the next version depends on the development work as part of the above mentioned project. Nevertheless, the authors suggest two options for consideration. The first option involves the addition of a new schema in the Domain Layer of the IFC data schema architecture, referred to as the 'Fire Safety Analysis Domain'.

The second option involves the addition of a new layer (called the 'Simulation Layer') on top of the Domain Layer of the IFC data schema architecture. This new layer would contain schemas for capturing data for various types of simulations performed (e.g. Energy analysis). A new schema for FSE based analysis can be added in this new layer.

Progress in work to support Step 3 - Enhance fire/evacuation modelling tools to support BIM

According to a recent online Survey of Pedestrian Evacuation Models [10], several evacuation modelling tools have functionality to import building geometries from BIM IFC files. However, the report did not indicate which specific tools have this functionality. An initial review of a small selection of commonly used fire and evacuation modelling tools conducted by the authors suggests that currently, the support for BIM data in these tools is limited and primarily concerned with the extraction of geometry data relating to the location of walls, doors and windows. The evacuation and fire modelling tools that are known to have some support for IFC file import are shown in Table 2. Please note, this is not intended to be a definitive list of all the fire and evacuation modelling tools currently available that have IFC data import capabilities.

Table 2. Evacuation and Fire modelling tools with IFC file import capability

Evacuation modelling tools	Fire modelling tools
ASERI[1] by IST GmbH, Germany [65]	ANSYS[2] by ANSYS, Inc., USA [69]
buildingEXODUS by FSEG, UK [12]	KOBRA-3D[1] by IST GmbH, Germany [65]
Crowd:it by accu:rate, Germany [66]	PyroSim[3] Thunderhead Engineering, USA [64]
Legion by Bentley, USA [67]	SMARTFIRE[4] by FSEG, UK [11]
MassMotion by Oasys, UK [61]	
Pathfinder by Thunderhead Engineering, USA [63]	
Pedestrian Dynamics by INCONTROL, Netherlands [68]	
STEPS by Mott MacDonald, UK [62]	

[1] The development work to add IFC file import capabilities in ASERI and KOBRA-3D is, at the time of writing, a work in progress according to the vendor.

[2] Support for IFC file import is through CADFEM extension for ANSYS.

[3] PyroSim can also import the material names and create surfaces with those names, but the material properties are not imported [70].

[4] The development work on importing an IFC file in SMARTFIRE is, at the time of writing, a work in progress with a command line application currently available that can read an IFC file.

IFC file import functionality in evacuation modelling tool buildingEXODUS

The buildingEXODUS software is one of the few evacuation modelling tools that have implemented IFC file import functionality. To achieve this functionality in buildingEXODUS, the authors have utilised a third party library. An IFC import tool, compatible with IFC, has been implemented and added to buildingEXODUS. It uses IfcOpenShell [71] and can read building geometry data. It has been tested for a small subset of the elements in the IFC file which the user can then selectively filter further. To highlight the functionality of the developed IFC import utility, a two-storey building, which is of a suitable level of complexity for the proof of concept demonstration of the prototype system, is used as an example. The population of the building consists of 150 visitors and four staff members. A screenshot of the visual representation of the Architectural model of this two-storey building created in Autodesk Revit is shown in Fig. 4.

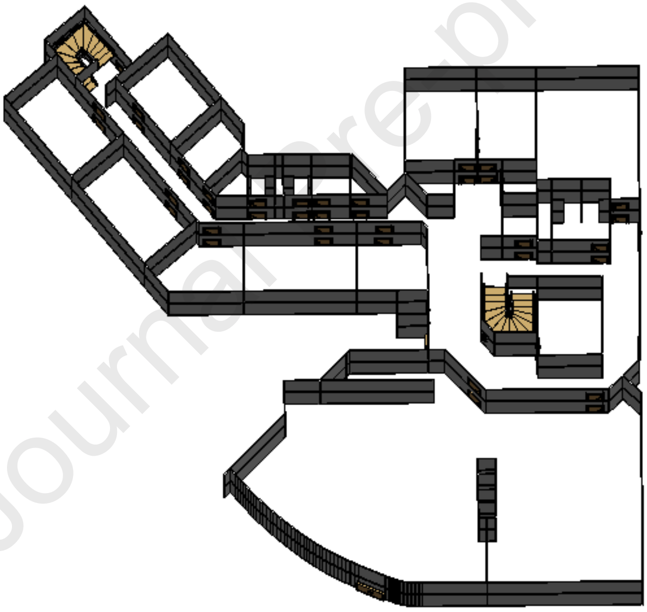
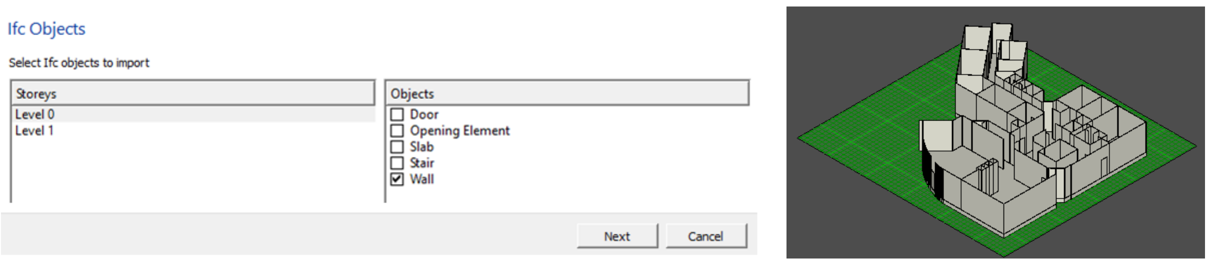


Fig. 4. Visual representation of demonstration building

It should be noted that, in Fig. 4, the floor/ceiling visualisation is turned off. This 3D model was then exported as an IFC file using the export feature in Revit. In buildingEXODUS, when importing IFC files, the users are presented with options to select the objects they want to incorporate in the model. The options presented when importing the IFC file of the building are shown in Fig. 5.



(a) Building Ground Floor available IFC objects for import in buildingEXODUS

(b) Building Ground Floor Cross Section view when importing in buildingEXODUS

Fig. 5. Ground floor of example building

The IFC file import functionality 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, automatic extraction of components, such as staircases and lifts to speed up model generation, location information extraction of smoke management components, and extraction of furniture elements. Furthermore, the automatic extraction of compartment/room connectivity will allow for improved occupant (referred to as an agent in simulation tools) spatial navigation, route decision making and cognitive models.

IFC file import functionality in fire modelling tool SMARTFIRE

For SMARTFIRE, a command line application and other support tools have been developed to read and extract geometry information from an IFC file to build a fire modelling scenario. Currently, this is not a fully automated process, and the user is required to manipulate the model data to select those geometry aspects to import or to provide additional information.

The current IFC import functionality in buildingEXODUS and SMARTFIRE, including the suggested future work, is in support of the existing BIM IFC Model. To support the future enhanced IFC Model, completion of Step 1 and Step 2 is required.

4. Evaluation of two-way data flow between FSE and BIM

To highlight several potential benefits of data sharing, a prototype system to evaluate simple two-way data sharing between BIM and FSE has been developed [53] which has been briefly described here. The conceptual design of the prototype system is shown in Fig. 6.

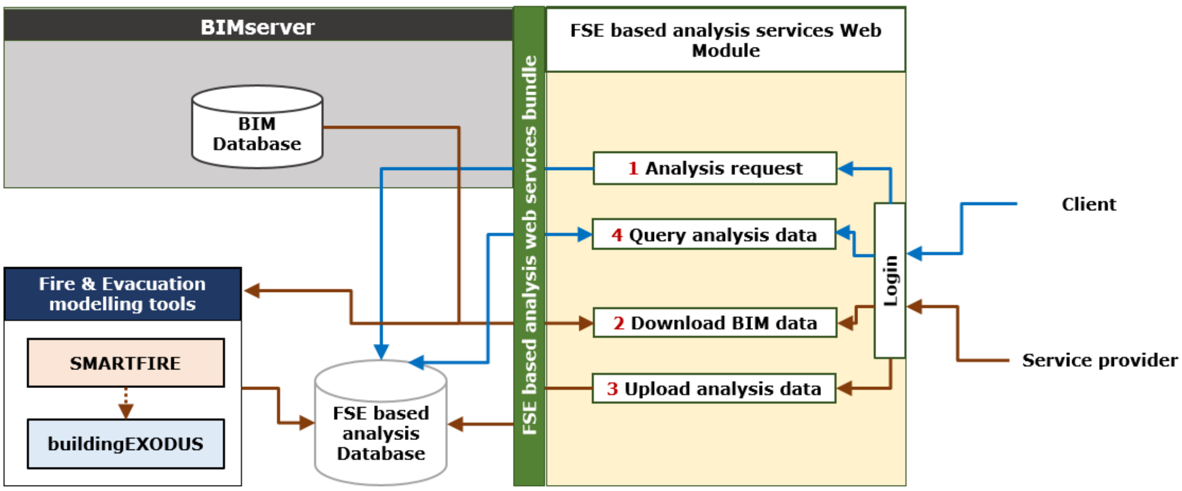


Fig. 6. Conceptual design of the system utilising BIM and Fire/Evacuation modelling tools

The main components of the prototype system shown in Fig. 6 are:

BIMserver: The National Institute of Building Sciences (NIBS) which is part of the buildingSMART alliance, has worked 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. Even though the cloud based BIM is currently at an early stage of interoperability research [72], several server based products utilising aspects of BIMSie are available. Some of these products are freely available such as the BIMserver [73], which is open source and offers a platform based on plug-ins and relies on IFC data stored in a database. Based on this, BIMserver was selected as a suitable platform to facilitate web services enabled data sharing as part of the prototype system.

Fire and evacuation modelling tools: The fire and evacuation modelling tools SMARTFIRE and buildingEXODUS were selected for this analysis. They were selected for analysis as they are broadly representative of the capabilities, data requirements and forms of output of many of the fire and evacuation simulation tools used by industry [74, 75, 76, 77, 78]. The authors are continuing to evaluate and review commonly used FSE simulation tools to ensure that a fully representative set of inputs and outputs will be included in the base definition for BIM extensions needed for FSE.

Performance-based FSE analysis database: The database was created to store simulation data and work as a component of the prototype system. The preliminary design of the database, as shown in Fig. 7, mainly focuses on the simulation output data and only covers a subset of the level of details that representative fire and evacuation modelling tools such as SMARTFIRE and buildingEXODUS respectively, can support. However, this can be expanded to capture more information (e.g. usage of stairs) It should be noted that for Fig. 7, no specific database design notation was used, and a simplified diagram has been presented to aid in clarifying the concepts. Also, the choice of the type of data is not necessarily specific to a particular tool, even though the evacuation modelling tool buildingEXODUS and fire modelling tool SMARTFIRE were used as the primary sources for information.

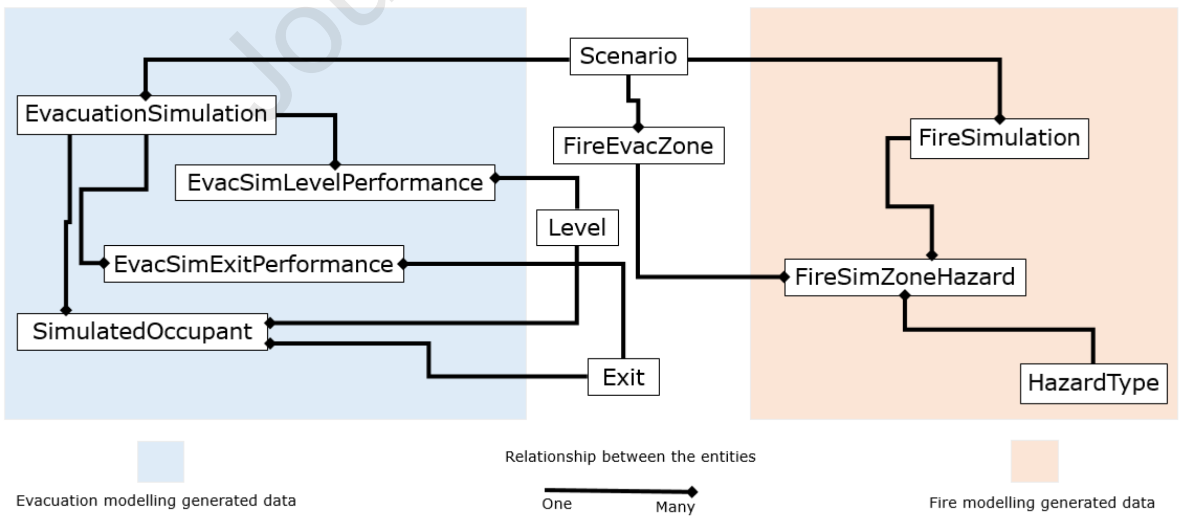


Fig. 7. Preliminary database schema design showing entities for performance-based FSE data

The entities shown in Fig. 7 are listed in Supplementary material Table S3 with some selected attributes and description. Using this database, it is possible to capture and share key analysis data. For instance, details of scenarios, simulations generated data such as exit performance, overall and simulated occupant level details, and hazards situations. There is provision for fire hazards since these can have a major impact on evacuation dynamics. In this preliminary design, associating a hazard with a zone (a region of space within the geometry where the fire hazard applies) approach has been used. However, other approaches can be catered for with some adjustments to the design. For the purpose of evaluation, this preliminary design was implemented in a representative Relational Database Management System.

Performance-based FSE analysis web services bundle: Several services as part of the performance-based FSE analysis web services bundle were created. These services were attached to the BIMserver and used to communicate with the database and provide the required functionality.

Performance-based FSE analysis services Web Module: A web frontend called 'FSE based analysis services Web module' was developed which uses BIMserver JavaScript Client API to call web services in the FSE based analysis web services bundle and establish communication with the BIMserver.

Simulation outputs from multiple scenarios, including their expert interpretation, can be added into the database. The client can then query these results and is able to see a comparison. These scenarios can be for the design phase or change in design due to a change in space usage, etc.

4.1 The prototype system in action

The prototype system is shown in Fig. 8 highlighting various steps of the two-way data flow using the demonstration building as an example.

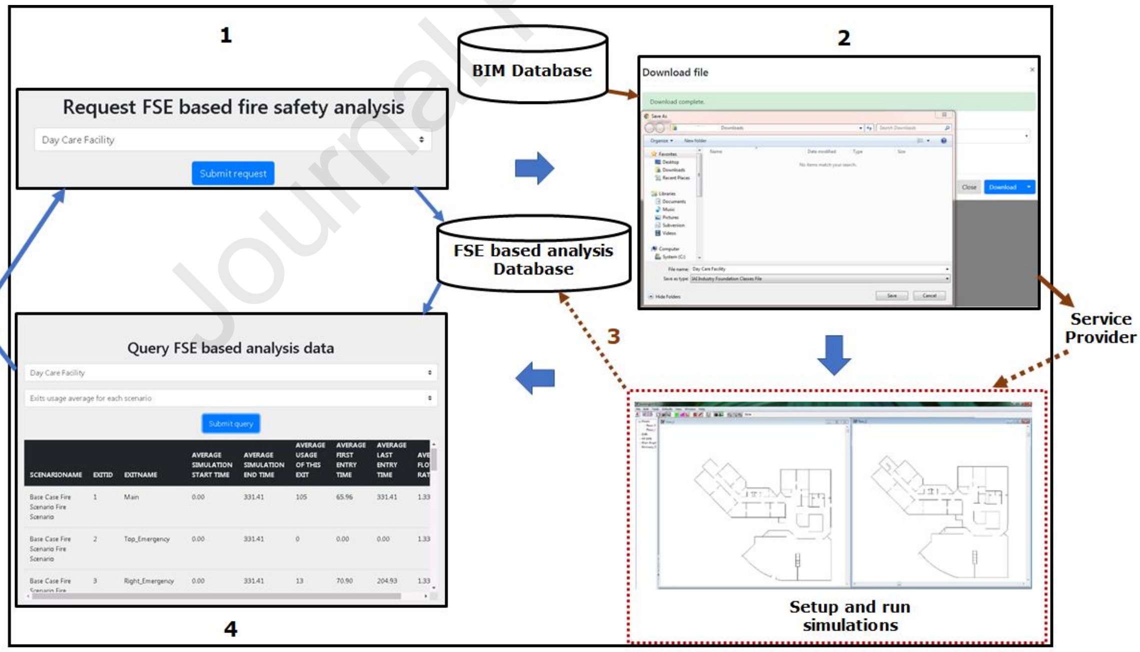


Fig. 8. Prototype system in action – BIM with FSE data sharing for the demonstration building

As shown in Fig. 8, in Step 1, the client submits an FSE analysis request using the Web-based front end. The service provider then downloads the building data stored in the BIM Database as an IFC file as part of Step 2. Before Step 3, there is a required (currently manual) process of setting up and running the simulations in fire (SMARTFIRE) and evacuation (buildingEXODUS) modelling tools (indicated by the red dotted lines), that is initiated by importing the BIM IFC data downloaded in Step 2. It is noted that this process is not part of the prototype system.

In Step 4, the client can view the analysis results through the web front end by selecting and running queries. For instance, this could include important FSE metrics such as: the overall evacuation simulations summary for each scenario, exits usage average for each scenario, average RSET value for each scenario, and ASET value for each scenario.

Currently, overall conclusions and interpretation of results for each scenario are added manually to the database.

Even with simple two-way data sharing, with limitations, the prototype system successfully demonstrates the following benefits of data sharing between BIM and FSE:

1. Client and service provider approach which offers ease in communication.
2. Audit trail of key communication steps are captured, which can be beneficial for future reference.
3. Data is captured, stored, and shared in a structured way.
4. Several Level 3 BIM concepts (e.g. server hosted single shared project model, use of standards such as IFC, and web services approach) were used by this system.

5. Discussion

The broad scope of FSE makes it extremely challenging to devise an all-encompassing design for an MVD to cater for the wide range of methodologies, tools and software currently in use in the application area of Fire Safety. It is also acknowledged that, to date, FSE has largely been conducted outside of the BIM development framework and as a result, BIM has not evolved to support or even to co-exist with the many needs of FSE. This presents many challenges, not least because FSE is also developing very rapidly as are the regulations and guidelines for using FSE in building design. The proposed approach to develop a conceptual strategy for two-way data sharing between BIM and FSE tools is pragmatic in that the MVD and software additions will be developed iteratively from relatively simple proof-of-concept definitions, and these will be extended to include the industry-wide and future-proof definitions. This process is facilitated by the development of BIM standards which allow software vendors to adapt their own software to the required information storage capabilities and feed into the process of standards development. The challenge then becomes to demonstrate to current and potential stakeholders that the proposed approach is valid, representative of industry needs and beneficial. The authors are currently involved in developing standards and enhancements for MVDs for FSE and writing a white paper to promote and explain the scope of this work. There is already considerable interest from key stakeholders in the FSE community as well as from engineering and software development organisations.

There is a huge effort required to bring the whole of FSE under the BIM umbrella. Previous work on this has only managed to encapsulate (albeit imperfectly) the geometry and some, but not all, of the building information needed by FSE. Also, none of the results of the FSE analysis is shared back into the BIM space. Consequently, FSE is a one-way process and partly decoupled from the building development and management lifecycle. This is the existing “world view” that this paper is working to change, both to highlight the problems with the current approach and to provide a workable framework and strategy to accommodate all the needs of the industry and the specific requirements of FSEs, whilst also providing the manifest benefits.

At present, with only a prototype demonstrator for the exchange of FSE information, the benefits of the proposed approach are largely theoretical. This will change with the realisation of the MVD for FSE and support for FSE results sharing with the other BIM users. In addition to supporting the "golden thread of information", a tangible benefit will be for automated design checking with FSE being able to determine when any proposed design changes or changes of building usage would trigger a change of fire safety status for the building, with a consequent need for re-evaluation of the fire safety. Other potential benefits will accrue due to the possibility of systemic integration of FSE within other building control and support systems – via the proposed data interface – that will allow for future developments such as smart building fire control for suitably automated buildings. Furthermore, the challenge of digitising the information related to buildings that were designed, pre-BIM, will be facilitated by having support for the mission critical FSE information.

A key benefit of the thesis proposed in this paper is that it more strongly associates the FSE design and regulatory approval process with the building design and construction process already encapsulated in BIM. This supports the Hackitt recommendation to preserve the digital golden thread of information. This not only means that the data is captured, but also that the FSE and regulatory process is more accessible to through-life building modifications such as change of usage or refurbishment. This may also have potential unintended consequences in that it may impact the way that Fire Safety Engineers and Regulators work and interact within the proposed new context. The suggested approach may also impact other aspects of building lifecycle and maintenance such as regular fire inspections, making inspections more straightforward and allowing the capture of fire inspection data within BIM.

This is also likely to have an impact on FSE's in their approaches to design checking as BIM and automation tools undertake some of the FSE's traditional jobs. Other industries, e.g. Automotive, have successfully adapted to such automation changes.

Once the service-oriented approach, highlighted by the prototype system in the previous section, is fully realised, it can provide effective and quick access to the required information. Also, it can serve as an important step in moving towards building automation with BIM by integrating with Building Management Systems (BMSs) as part of the future Smart Building technology, in incident management applications such as Active Dynamic Signage System [13]. The proposed strategy will assist in reaching the goal of a fully integrated single building database containing all the building data from the FSE perspective. This will allow FSE to contribute not only during the building design but also for operational phases as well as supporting a change of usage or redevelopment, as part of integrated BIM Level 3.

6. Concluding comments

This paper has identified key challenges and limitations facing the use and involvement of performance-based FSE within the context of BIM. The current BIM IFC Model does not fully support the input data required for FSE and also there is no FSE specific filtered view of the that data. A further significant omission is that there is no explicit provision for the essential safety analysis output data generated by the fire and evacuation modelling. Furthermore, a minority of the fire and evacuation modelling tools have only limited and basic support for extracting some of the BIM information (i.e. the building geometry). In response to these issues, a practical conceptual strategy for enhanced data sharing between FSE and BIM has been proposed along with the development work in its support has been presented. The proposed strategy provides 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.

Some initial progress on the development of the proposed strategy has been reported. This includes preparing a collaboration project proposal for BIM Standards Organisation buildingSMART with international project partners. To assist in information gathering for the data requirements for FSE that can assist during the initial phase of the collaboration project, an initial list of data requirements has been produced by the authors. Also, the implementation of the building geometry extraction from IFC into the evacuation modelling tool, buildingEXODUS, has been demonstrated, albeit with some limitations. A command line application for extracting building geometry from an IFC for fire modelling tool SMARTFIRE has also been developed. Furthermore, to demonstrate simple two-way data sharing between BIM and FSE and to highlight some potential benefits of the approach, a web services-oriented prototype system has been developed. An important component of this prototype system is the preliminary database design used to capture and share the fire safety analysis data generated by the fire and evacuation modelling example tools, SMARTFIRE and buildingEXODUS.

There are many clear benefits of tightly integrating BIM and FSE including, iterative design checking, the efficient use of FSE beyond the design phase, including life-cycle applications and inherent support for smart building fire safety applications. The conceptual strategy presented in this paper provides a means of achieving enhanced data sharing between BIM and performance-based FSE which will provide an informed future direction for BIM development within the FSE context. Also, the development work in support of this strategy will contribute, particularly in the requirements analysis part of the proposed international collaboration project, that will be a step towards achieving the recommendation in the Hackitt Report for a "golden thread of information" from the performance-based FSE perspective. However, the project has also identified that there is a need for FSE practitioners, regulators, and other stakeholders to be more involved in the future development of FSE with BIM and with the BIM community. The work presented in the paper is a step in that direction.

Key aspects of further development include:

- Extending the data requirements to a representative subset of FSE software and abstracting to a standard definition so that FSE software developers can adapt to the defined standard interface.
- Extending the output requirements to support the needs of building regulators, building management and other stakeholders who have a need for the data.
- Capturing and storing information about how the FSE modelling was performed. This will facilitate a better understanding of how the FSE was used to make decisions and enable alternate fire safety practitioners to use other FSE approaches to arrive at similar fire safety conclusions. This will assist both third party scrutiny and in the support of change of usage/re-development.
- Reach out to the entire FSE stakeholder community worldwide to develop a better understanding of how BIM is currently being used, what the perceived FSE needs are for BIM and what are the perceived challenges to uptake and usage of BIM.
- Explore how the prototype system can be extended to include automation in design error checking and change management.

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- Identification of current limitations of BIM for FSE.
- Identifies the need for a strategy to integrate FSE into BIM.
- Provides a practical road map for integrating FSE within BIM.
- Proposes changes to the IFC Model for improved support for FSE.
- Demonstrates two-way data sharing between BIM and FSE using a prototype system.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: