International Journal of High-Rise Buildings
December 2021, Vol 10, No 4, 251-263
https://doi.org/10.21022/IJHRB.2021.10.4.251

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

BIM and Fire Safety Engineering – Overview of State of The Art

Anne Davidson[1] and John Gales[1]

[1]*Department of Civil Engineering, York University, Canada Corresponding authors: John Gales and Anne Davidson*

Abstract

Fire safety engineering is a critical specialization to include in the design of a tall building yet is often excluded from the Building Information Model (BIM) and integrated design process. The design of fire safety systems is interdependent with building/structural geometry, HVAC, mechanical, and electrical systems. A BIM is a 3D visual representation that stores data on these kinds of systems. The compatibility between BIM and fire safety design seems obvious yet has received a dearth of attention in structural (fire) engineering literature. The authors herein have reviewed over 40 recent papers on utilizing BIM for fire safety engineering, focusing on contemporary literature to obtain a more up-to-date review of the state-of-the-art. The resulting trends, technologies, research gaps, and methodologies are presented in this paper. Adoption of BIM in fire safety engineering is slow and behind other disciplines which may be improved if research involved more industry partners. For BIM technology to reach its potential, industry manufacturers need to provide high LOD fire BIM objects, fire engineers and researchers need to collaborate on future advancements, and building owners/management need to be educated on how to use the benefits provided.

Keywords: BIM, fire-safety, literature review

1. Introduction

Fire safety engineering is one of the most critical specializations to include in the design of a tall building yet is often excluded from the Building Information Model (BIM) and integrated design process. Fire safety systems are interdependent on building/structural geometry, HVAC, mechanical, and electrical systems. This requires the professions to collaborate early on with multiple disciplines for a building optimization to be possible. To save time and ensure accuracy, the fire safety engineer and practitioner need to know about design changes from other disciplines as they happen. BIM is an opportunity to streamline this kind of collaboration but is not being considered for fire safety in industry.

The fire design process can range from a prescriptive approach to performance based. The prescriptive approach can be prone to errors but is often a less laborious, faster design. Performance-based design allows opportunity for new and more economical solutions to be utilized. The simulations and analysis involved however are a time consuming and laborious process (Smith and Teravainen 2018). Fire safety does not stop at design. It is important for the building's entire life cycle that life safety is maintained. This requires consideration of the construction phase, monitoring of fire safety equipment, and emergency evacuation management.

†Corresponding author: John Gales and Anne Davidson
Tel: +416-736-2100, Fax: +416-736-2100
E-mail: jgales@yorku.ca & anned@yorku.ca

Building Information Modelling (BIM) can be utilized to manage the fire safety of a building during all phases. Projects that use BIM increase in efficiency while reducing conflicts, error, and miscommunication (Ozturk and Eraslan 2019). BIM is a 3D visual model capable of organizing and storing data. BIM is not a software or a data set meant just for design. Algorithms can analyze and process the data to provide design options, check codes/regulations, create material lists, etc. A fully developed BIM would contain all the information from various disciplines for a fire safety engineer. The compatibility between BIM and fire safety design seems obvious yet has received a dearth of attention in structural (fire) engineering literature due principally to the confidential nature of the projects for which it has previously been applied. A mis-understanding of BIM has resulted in limited views on its application and capabilities (Johnston 2021). This has resulted in BIM's adoption in fire engineering being slow as benefits and lessons learned are not realized or shared by practitioners.

Once the Fire Safety Engineering (FSE) sector embraces BIM, the FSE may be included in a projects integrated generative design process. Inclusion in this process would allow buildings to be optimized to include fire safety effects from the beginning of the design process. This would allow for new alternative solutions to be generated based on logical rules and design objectives (Lovreglio, Thompson and Feng 2021). Other AEC sectors have been taking advantage of this BIM tool and although the inclusion of FSE would likely have significant effects on

overall life safety in a building, it has been lagging in technological advancements and industry understanding (Lovreglio, Thompson and Feng 2021).

The purpose of this paper is to provide a holistic overview of contemporary advancements and technologies related to using BIM for Fire Safety Engineering. A summary and comprehensive analysis of existing published research and projects where BIM is used with fire safety engineering is provided. The analysis identifies to the reader what frameworks are used for various BIM integration purposes. The frequency of specific software use is also highlighted, providing the reader with an overview of what has been working and identifying research trends. The authors provide a road map indicating when certain BIM and fire integration methods are most appropriate during the life cycle of a tall building. This paper will provide, for the first time, a foundation of knowledge and direction to proceed with planning how to integrate fire safety design into a dynamic BIM for their next project.

2. Literature Review

The literature review began by indexing articles and papers on how BIM technology has been used for fire safety engineering. Since technology changes rapidly, priority was given to more recent literature (as of 2021) which may have more up to date, state-of-the art methodologies for integrating fire safety and BIM. From 2019-2021, a surge of literature was published regarding the subject, indicating that industry has identified the gap and is working to resolve it. This therefore builds upon the authors previous efforts to undertake such a gap analysis. All the literature was retrieved from online search databases such as Google Scholar and Omni. Journal papers, conference papers, and trade magazines were all considered. After a paper was identified, a preliminary screening was done to ensure that the document specifically related to utilizing BIM for fire safety engineering. During review, software, sponsors, BIM uses, and BIM applications were manually catalogued. Once the literature was reviewed, it became evident that BIM technology was being used for a variety of fire safety purposes, spanning from a building's conception to a fire event. The various applications of BIM and fire safety that emerged from the study make up the subsections below. They have been organized in sequential order of their application from conception to fire emergency management, indicating where the technology has been appropriately applied. To identify research trends and areas where research might have the greatest future impact, the details of technology used such as software, file formats, programming languages, etc. were examined. The subsections below identify, describe, and discuss the latest technological advances in digitizing the field of Fire Safety Engineering.

2.1. Fire Smart BIM Objects

Smart BIM components are objects located within the BIM such as doors, windows, fire alarms, fire detectors, etc. and contain additional information on the component's performance. For example, a beam could contain a property parameter such as maximum span, which allows designers to easily choose member sizes (Patlakaset al. 2015). Similarly, a smart BIM component can contain parameters regarding Fire Safety including performance requirements and material properties such as the identification of fire separation walls that can automatically restrict/limit wall penetrations (Smith and Gales 2016, Shino 2013). Embedded parameter needs are still being assessed and identified as research progresses. Most software have a unique way of describing BIM objects and their parameters (Spearpoint and Dimyadi 2007). For the object to be compatible accross the various available BIM platforms, it should be described/ classified in a standard and/or conventional format (Wu and Zhang 2019). Researchers have mainly applied COBie and IFC open standards (Chen et al. 2020). A common misconception is that these are two different standards but in fact, COBie is actually a Model View Definition (MVD) data specification for the IFC model standard (Potatacas et al 2014). Industry Foundation Classes (IFC) is the best available and most widely utilized standardized way to categorize digital elements and enable automated data transfer, which is essential for the data stored within the object to be useful (Gao and Xue 2017). IFC models, however, can be misused and improperly classified, which Wu and Zhang have created an algorithm to fix. Currently, IFC standardization specific to fire performance parameters is yet to be developed and currently under research (Eftekharirad 2019, buildingSMART 2021). For the time being, practitioners have been manually adding required parameters using formats specific to the software being used or creating an IFCExtension. A demonstration can be seen in Figure 1 where a timber column object has been updated to contain the effect of a reduced cross-sectional area after a one-hour fire by utilizing an arbitrary charring rate of 0.88 mm/min.

A BIM object can be developed to various Levels of Detail/Development (LOD). The LOD for the preliminary design phase includes geometry, location, quantity, and type information. The LOD for the detailed design phase also includes materials, performance requirements, fire resistance, and functional specifications. In the construction management phase, the LOD also includes but is not limited to manufacturing and installation data, technical data sheets, operating and maintenance manuals, and certificates of compliance (Amaro et al. 2017). Objects within a BIM are meant to be updated/replaced as the design progresses, allowing a digital twin of the building to exist throughout its lifecycle.

Developing smart objects from scratch is a timecon-suming process which has urged manufacturers to develop BIM-compliant objects containing information

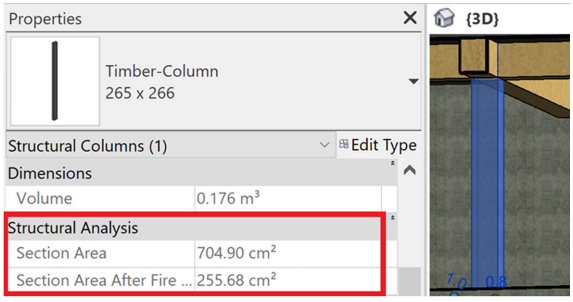


Figure 1. Timber column BIM object embedded with fire research data. (author's analysis)

on their fire protection products (Amaro et al. 2017). Currently, online BIM libraries exist containing smart windows and doors which include energy performance data. Adding smart BIM objects to online libraries is consistently under development and remains a recommended area of further advancement (Staub-French et al. 2018).

2.2. Automated Code-Checking

Researchers, practitioners, and software developers have successfully been able to automatically check BIMs for code compliance. Automated code-checking is being used in many fields due to the increased efficiency, taking as much as 80% less time than manual methods (Beltraniet al. 2018, Ren and Zhang 2021). This process however requires a lot of specific data not always included in the BIM, increasing the need for higher LOD BIM objects (Kincelova et al. 2020). Consequently, few tools are available that extract fire safety data from BIM objects and assess the model for code-compliance.

Most code-checking applications utilize the Application Programming Interface (API) included in BIM platforms to extract and manipulate element properties. The common API for Revit is the visual programming tool Dynamo, and for Rhino, Grasshopper is often used (Khan et al. 2020). This has allowed the success of many case studies which perform design calculations according to code, identify non-compliant elements, and provide visual feedback (Eleftheriadis et al. 2015, Porto et al. 2018).

In 2018, the state-of-the-artfire code checking applications were still only able to utilize BIM's geometry with the exception of an object's Fire Resistance Rating (FRR) specification (Porto et al. 2018). Earlier research done on developing and testing code-checking applications, identified a need for quality assurance processes (Choi et al. 2014). Ren and Zhang address this in their 2019 and 2021 evacuation code checking research by developing an algorithm to check that the IFC format of the BIM contains the necessary parameters. Many authors who developed and applied code-checking applications within a BIM, consensually recommend future development in increasing LOD BIM fire objects, functionality/performance of code-checking, translation of regulations to computer language, and focus on quality assurance processes. Currently, many international, federal, and regional building code agencies are in the process of translating written code to rule-based formats which can be easily programmed.

2.3. Structural Fire Dynamic Integration (internal and external)

Numerical and algebraic fire calculations can be performed within a BIM platform. Smith and Gales (2016) suggested integrating fire as a load case in BIM. The concept of 'fire load' indicates the quantity of heat liberated per unit area when a building and its contents are completely burnt (Amaro et al. 2017). Amaro et al. (2017) integrated fire load calculations directly into the BIM model by introducing the characteristics of materials (e.g. weight and specific fire load) and by setting the algorithm in the materials schedule. Later, calculating time-temperature curves for various compartments was also programmed into the BIM although this can require more material property extraction. The calculations will be incorrect if the parameter and boundary conditions are incorrect, exemplifying the need for quality assurance processes. It is also important to consider that calculation methods for fire loads and time-temperature curves may differ across jurisdictions. Even though the calculation process can be automated, it is still essential that experienced professionals are involved. More complex and dynamic fire calculations require an external platform for simulation. There are over 160 different modelling tools for smoke and fire simulations (Ralph and Carvel 2018). The most common fire/smoke simulation tool is Fire Dynamics Simulator (FDS) by NIST which is an open source Computational Fluid Dynamics (CFD) based program which has been validated and accepted in industry. Automated direct data transfer of fire parameters beyond geometry for performance-based fire design simulations is difficult and rarely achieved (Kincelova et al. 2019). As a result, engineering models are created from scratch instead (Ren and Zhang 2021). Although automated synchronization between models has been known to cause large reductions in time, an analysis by Vilutiene et al. (2019) of 369 papers on BIM and Structural Engineering indicate that most research has been focused on conception with little application of BIM capabilities (Eleftheriadis et al. 2015, Vilutiene et al. 2019). This redundant effort is a consequence of the fire and smoke simulators' incompatibility with standardized BIM formats such as IFC. This issue is being partially addressed with BuilingSMART's IFC4 Software Certification recognizing software which successfully uses IFC data structures (BuildingSMART 2021). Although fire simulation software developers have expressed BIM compatibility in recent releases, according to the BuildingSMART database, none have any kind of IFC certification. BuildingSMART International currently has an active committee working on a MVD for FSE. Involved researchers Siddiqui et al. have been working on this data specification that would allow full support for fire safety simulation input and output data.

Currently, only geometry import is accepted by some FSE tools and there is no framework for simulation results to exported back into the BIM (Siddiqui et al. (In Press)).

Even the most recent and resourceful applications of geometry transfer require multiple steps and third-party software to properly mesh the surfaces. An example of this is the workflow used to transfer the geometry of Canada's parliament building to a Virtual Reality (VR) platform took eight steps and at least two third-party software programs (Pybus et al. 2019). Successful direct-integration on the other hand, tends to be due to the effectiveness of the algorithm developed to automatically reassign IFC-data file names. The research that attempts this varies dramatically in methodology and concludes with much room for improvement. The work of Shi et al. (2019) successfully automated data transfer from Revit to PyroSim (an FDS interface) and back into Revit. However, structural analysis is still missing from the framework. Other works have included Agent Based Modelling (ABM) within the framework to combine both fire and evacuation simulations as well as floorplan layout optimization (Sun and Turkan 2019, Cheng, et al. 2019). These frameworks struggle with integrating the results back into the BIM and still involve numerous steps which could be further simplified. Many of the fire modelling research efforts tend to be redundant due to a lack of communication and collaboration (Ralph and Carvel 2018).

2.4. Emergency Evacuation Integration (internal and external)

During an emergency, the most critical concern is for building occupants to evacuate safely. In a real fire scenario, the chances for safe evacuation reduce significantly with time. Evacuation simulations can calculate/predict occupant behavior during an event and evaluate the resulting risks for building design improvements. The required safe evacuation time (RSET) is a common tool for determining the life safety of occupants in a building on fire. This evacuation time can be calculated/addressed using prescriptive methods or performance-based methods. Prescriptive rule-based methods can be easily integrated with BIM by using code-checking and BIM platform API's for programming route calculations (Fu and Liu 2019).

Integrating performance-based evacuation with BIM has been more successful and frequent than fire dynamics. Unlike fire dynamic simulations, evacuation simulations only need the geometry of the building and not necessarily any other parameters, simplifying the complete integration requirements. Visual programming APIs are frequently used to manually build algorithms that extract and convert geometry into readable formats and program results back into the BIM (Beltrani et al. 2018). Once the geometry data is extracted, it is often then used as boundary conditions for an Agent Based Model (ABM). The resulting simulations can detect blocked egress routes, safest egress route, shortest route, and identify most critical design fire initiation locations (Mirahadi et al. 2019). The complexity of evacuation simulations is principally due to the complex nature of human behavior. How humans respond within a building can change according to geometry, number of exits, size of pathways/exits, signage, previous building layout knowledge, etc. (Guo et al. 2020). Due to computational costs, evacuation models often exclude simultaneous dynamic fire and smoke simulations. The shortest path is not necessarily the safest or best performing path, creating need for hybrid models which are used to thwart this trade-off, providing a more feasible solution (Ronchi et al. 2019, Deng et al. 2021).

Because human nature is difficult to define and predict, gamified BIM (see Section 2.8 Extended Reality and Fire Safety) has been used to extract human behavioral data in attempts to improve the behavioral prediction accuracy. Studies have shown that with proper participant vetting this can improve the database that serves as the foundation to evacuation modelling theory. In future research, additional data that could be obtained from the BIM and used during evacuation simulations is the effect of communication information (fire alarms, lighting, etc.) and occupant information (demographics and use habits).

2.5. BIM and Construction Fire Safety Design

Around 6,400 structural fires (four deaths) occur per year in the USA during construction when designers tend to overlook fire safety management (Campbell 2020, Khan et al. 2020). Fire extinguishers tend to be the only fire safety mechanism in place on a construction site (Khan et al. 2020). A tool developed by Khan et al. (2020) aims to solve this by extracting site rules from the BIM and code, identify fire fighting equipment for installation, bill of quantity for fire fighting equipment, and an escape route plan using the Dulaney triangulation pathfinding algorithm within Revit's API. The escape route plan and fire scenarios are simulated. Escape routes during construction can be evaluated at different phases by considering a BIM that is at least 4D (Marzouk and Daoor 2018). The authors only found two papers related to this subject. In the future, BIM could utilize safety indexes of site instructions used by construction management to identify and mitigate fire risks before construction begins. Perhaps machine learning could correlate construction methods with fire risk and the BIM AI could suggest alternative designs. Construction is now starting to provide an as-built virtual reality that could also be analyzed for fire risk such as identifying combustible materials close to a heat source.

2.6. BIM and Fire Safety Operations

The benefits of a matured digital twin BIM include better property and infrastructure management, including that of fire safety. A digital twin is a virtual replica of what is built. It is a dynamic BIM which processes live

data and gives feedback to the building. So far, there have only been preliminary studies of digital twin's application to fire safety (Chen et al. 2020). These studies include automatic processing/monitoring of danger/fires and assessing the number and location of people within a building by evaluating sensory data (Liu et al. 2020, Ma and Wu 2020). A building manager can virtually identify temperature, light, smoke, and CO_2 levels in each room. Should any levels breach a specified limit, cameras can be used to identify the severity of the situation (Ma and Wu 2020).

The operation management platform can notify personnel when a fire extinguisher needs to be inspected or manage scheduling of fire drills. Researchers have been able to create apps which can link equipment on site to the BIM using RFID and/or UUID identification tags (ex. bar codes). The Augmented Reality (AR) displays necessary inspection forms and updates the data. This allows for virtual information management of FSE inspections regarding fire extinguishing equipment/systems, alarm equipment, refuge escape equipment, fire rescue equipment and protective equipment (Chen et al. 2020). For this to be possible, the LOD of smart BIM objects should be extremely advanced during operation phase of a building's lifecycle. The digital twin should include access to maintenance and operation manuals and certifications for various building components. This has been applied to Mechanical, Electrical, and Plumbing (MEP) in the past, whereas digital fire safety systems such as fire detection, sprinkler systems, and alarm systems are currently under development. To maintain BIM quality, the digital twin should limit visibility to certain users and only include information needed to run the infrastructure management platform smoothly (Amaro et al. 2017).

Sensory data and communication devices can update the BIM or be updated by the BIM by utilizing Internet of Things (IoT) technology (Chen et al. 2018). This allows individual control over building components. IoT can also allow for simultaneous data updates, allowing simulations to be run in real time. This provides opportunity for identifying potentially life-threatening maintenance jobs such as repairing sprinklers should water reserves be too low.

2.7. BIM and Fire Rescue

When a fire occurs in a building, BIM can be used to enhance the fire fighting, evacuation, and rescue efforts. Accurate decision making is important for evacuees to choose the safest path to exit and for fire fighters to rescue people as quickly/safely as possible. Decision making is susceptible to human error and can have negative impacts on evacuation/rescue times. Evacuees can be exposed to dangerous carbon dioxide levels, especially near the end of an evacuation (Mirahadi and McCabe 2021). To improve the evacuation conditions the fire must be identified early on, occupants and fire departments notified quickly, safe evacuation must be aided, and trapped or stay-in-place occupants must be located. The pre-evacuation time can be improved by quickly identifying the fire and disseminating detailed information to the occupants early on. The evacuation time can be improved by providing detailed instructions for wayfinding. Search and rescue efforts can be improved by providing occupant locations to the rescue team. Another consideration is the safety of the fire fighters. It is important to know the progression and whereabouts of dangerous levels of temperature, toxic gases, CO_2, and smoke. Fortunately, there are a few ways BIM can help with these.

BIMs provide a central intelligence system that when used dynamically, are constantly being updated with sensory input and updating communication devices within the building with fire safety information. This can command an optimized evacuation. To aid the evacuation, communication devices such as speakers, alarms, lighting, Active Dynamic Signage Systems (ADSS) and mobile devices can routinely be updated with fire safety information during an event (Mirahadi and McCabe 2021). When occupants are given clear instructions to the safest path, they behave more rationally, more efficiently, and are more stable (Ma and Wu 2020). An application of this is when ADSS is automatically updated with directions which prevent people from heading towards danger or opening doors that compromise fire compartments. A system developed by Ma and Wu (2020) sends an SMS to the occupants notifying them of a fire and having them indicate their choice to evacuate, stay put, or fight the fire. An app is updated with fire locations, fire safety equipment, the safest egress path, and/or location status. All this infor-mation is retrieved from the BIM and can be continuously updated. Information on occupant and fire/smoke conditions can be retrieved from the building to update the emergency status. Simultaneous data updates allow simulations to be run in real time to inform fire rescue teams about visibility, CO_2, flame spread (Chen et al. 2018). This allows fire rescue to visualize fire spread and occupant locations within a 3D model of the building. There have been little studies however on how real fires might affect Wi-Fi and internet capabilities, which allow the real-time data updates to be possible. Therefore, dependency on such systems would require further research.

The safest path needs to be calculated quickly while an emergency is occurring, making numerical solutions more effective for unpredicted scenarios than evacuation simulations (Mirahadi and McCabe 2021). Research in this area has shown a preference for Dijkstra's algorithm (Mirahadi and McCabe 2021, Ma and Wu 2020, Bayat et al. 2020). This algorithm can use geometry and occupant locations extracted from the BIM. This can be done automatically when an emergency is declared. The calculations can be re-iterated as the model is updated with more current sensory data. The downside of this is

complicated factors such as crowd density cannot be fully considered during an event but should have been previously considered in the design phase. An alternative is to have different fire scenarios simulating while the building is functioning and when an event occurs, it is matched to the best-fit simulation (Mirahadi and McCabe 2020).

2.8. Extended Reality and Fire Safety

Extended Reality (XR) refers to Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR generates a realistic environment with visuals and sounds and a representation of a user's presence in the environment. AR is where artificial information can be accessed in reality. An example of this is when a building manager scans equipment and then gains access to information about it via mobile device. MR attempts to combine VR and AR by making the digital content interactive with reality. This is a very new type of XR with no defined parameters and little existing applications (Alizadehsalehia et al. 2020).

Gamified BIM is an emerging field in which BIMs are imported into a gaming engine to simulate a virtual reality (Selin et al. 2019). Gaming engines have been developed to be superior at simulating virtual realities with less computational cost and more realistic graphics (Ruppel and Schatz 2011). In more recent years the AEC industry has adopted it for creating virtual realities that help visualize the interior spaces, construction, evacuation scenarios, fire simulations, and building management (Selin et al. 2019). Recently gamified BIM is being utilized as the building's platform for maintenance and operations as a way to simplify the database, making it practical for everyday use and easy training (Andrews 2020). For BIM fire technologies to work, they must be intuitive to use.

One of the earliest applications of Gamified BIM for fire safety was by Ruppel and Shatz's (2011) serious game that realistically simulates structural fire scenarios and extracts data to assess human behavior of users. The game environment includes fire, smoke, explosions and structural damage defined by FDS boundary conditions. There are numerous other serious games taking similar approaches that currently provide reliable results and realistic visualization effects (Guo et al. 2020). Lu et al. (2020) develop a serious game for training fire fighters where BIM founded geometry, a structural model, and an FDS model were combined in a game engine. Deng et al. (2021) created an Augmented Reality (AR) that guides fire fighters through smoke and the building's layout towards the fire location. Some researchers argue that VR should not be used in practice to simulate evacuations due to lack of validation (Ronchi et al. 2019). As the technology progresses, other researchers have been able to show that if participants are properly vetted before simulation, ensuring that it will mimic reality, the data retrieved can be quite accurate. Gamified BIM is on the way to become a more reliable, accurate, and consistent solution to engineering simulations as model validation and increased efficiency emerge.

3. Literature analysis

Table 1 shows the analysis of 39 studies that were done on integrating BIM with Fire Safety Engineering. These studies do not include literature reviews (8 studies). Listed from the oldest studies of the sample (2007) to the newest (2021, time of writing), trends in research efforts can be seen. For example, earlier years tend to focus on integrating fire calculations with BIM, while there was a surge in integrating BIM with evacuation calculations in 2019. Case studies used to demonstrate the research are more frequent in later years, indicating that the technology is improving from concept to use. There also seems to be an increased preference for internal integration in more recent years, eliminating the need for data exchange. Papers in 2019 focused more on performance-based design applications while prescriptive approaches have more available solutions in the market (software). Very few papers have a mathematical approach or analysis which suggests that research is not quantifying the benefit or faults of merging fire safety with BIM. Although the other BIM integration applications demonstrate the increased data acquisition/analysis, building fire code checking is the only application where research has clearly defined the cost-saving benefit. This is critical information for industry if the research is to be utilized in future tall buildings. In fact, only 8 out of 49 papers that the authors reviewed had industry partner contributions. This suggests a potential for a significant disconnect between what researchers think industry needs and what is actually needed, contributing to why BIM is not being fully utilized by fire safety engineers.

Figure 2 shows the primary focus areas of the research being done on integrating BIM with fire safety. In this figure, it is clearly defined that fire evacuation simulations

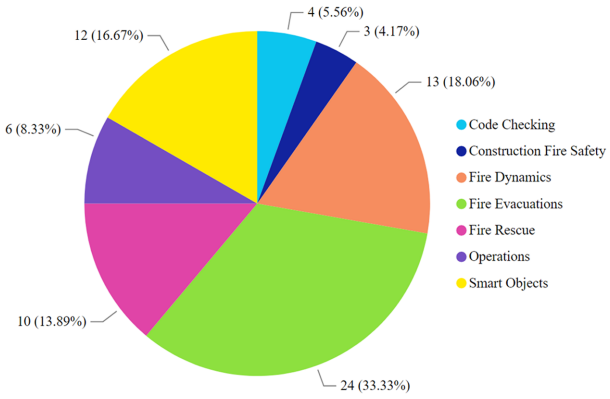


Figure 2. Areas of research focus.

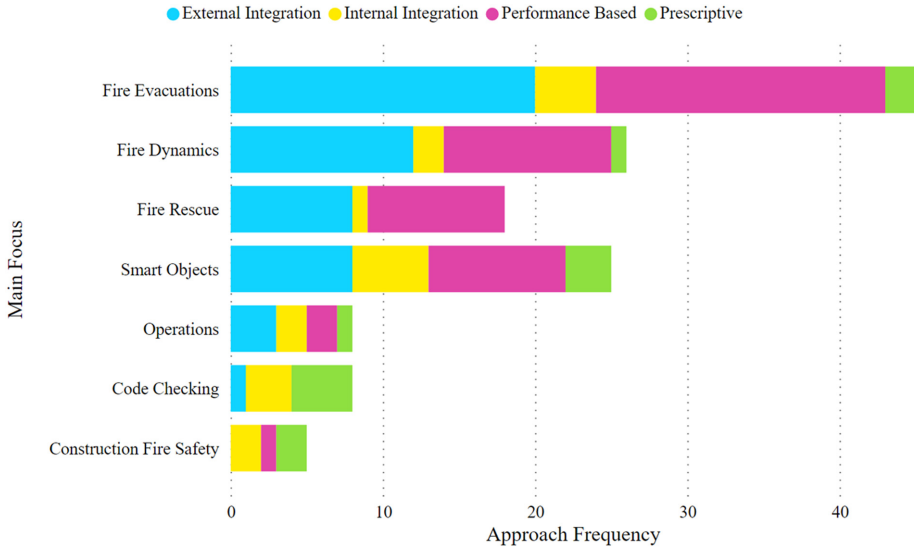


Figure 3. BIM integration with fire approaches.

are the most popular for BIM integration. Fire smart BIM objects and fire dynamics follow. Construction fire safety is the most in need of future research with only two papers having been identified. Out of the authors' sample, code-checking is also under-represented, but this could be due to the fact that it is already in use in industry so research regarding this topic is likely more frequent in earlier years than the authors' focus. Fire rescue and safety operations are quickly progressing in recent years. Many digital twin platforms are now being advertised in industry (such as ARUP's Neuron) but none advertise fire safety management (to the authors knowledge).

By counting the frequency of framework approaches relative to the primary focus of the BIM integration, it can be seen in Figure 3 what method is most prevalent in literature. Since both internal and external integration and prescriptive and performance-based can be utilized in one study, the percentages are not interdependent. Smart Objects for example, similarly use both internal and external integration. There has been more focus however on developing smart BIM objects for performance-based design. 75% of the sample researching code-checking used internal integration methods, eliminating the need for data exchange. On the contrary, 92% of the fire dynamic integration with BIM uses external integration. Construction safety and code checking both predominantly utilize internal prescriptive integration approaches. From Figure 3, prescriptive design tends to be integrated internally within the BIM, while performance-based tends to use external integration requiring data exchange.

Technologies being used by researchers for integrating fire safety with BIM is summarized in Figure 4. Autodesk Revit is the most used BIM platform along with its built in API Dynamo. The API is commonly used for code-checking, fire safety operations, and fire rescue. PyroSim is the most used fire simulation tool for integration with BIM and IFC is the most used data exchange format. The evacuation calculation tools are fairly distributed in their use, which may suggest that the evacuation research community is more in tune with making the calculation process compatible with BIM.

4. Discussion and Future Research Road Map

Growing technology can bring many benefits to the AEC industry. With respect to fire safety engineering, BIM can allow for automated code-checking, manage/automate fire safety operations, store simulation results, and provide a platform for fire emergency management. Simplified calculations for fire and evacuations can be performed within a BIM as well. From analyzing the literature however, there is a need for more research on extracting fire parameters from a BIM and making simulation tools truly interoperable with BIM platforms. Currently, the external integration process involves many time-consuming steps, leaving room for error. The BIM is however still useful for providing simulation tools with the building's geometry. The literature reviewed for this study was able to apply fire-BIM integration throughout the entire life cycle of a building. The authors have summarized this in Figure 5.

Before beginning a new project, the data management plan, quality assurance processes, and permissions must be decided on. Everyone in a project must agree for example that they will use IFC classification for their models. If information is missed, it must be quickly identified (Ren and Zhang 2021). Project stakeholders must be notified when a team makes a change in the model. Deciding this ahead of time provides structure to the team, reducing error, miscommunication, and time. Too much information and design changes can drive up

Table 1. Analysis of studies regarding the integration of BIM and fire safety engineering

Year	Author	Primary Focus							BIM		Design		Output		
		Smart Objects	Code Checking	Fire Dynamics	Fire Evacuations	Construction	Operations	Fire Rescue	Internal Integration	External Integration	Prescriptive	Performance-Based	Conceptual	Numerical	Case Study
2007	Shearpoint & Dimyadi			v						v		v	v		
2011	Ruppel & Shatz				v					v		v	v		
2013	Shino	v													
2014	Choi, Choi, & Kim		v		v					v	v				
2015	Wang, Wang, Wang, & Shih	v			v		v			v		v	v		v
2016	Smith & Gales			v					v		v		v		
2017	Amaro, Raimondo, Ebra, & Ugliotti	v		v					v	v		v	v		v
2017	Gao & Xue	v		v						v			v		
2018	Beltrani, Giuliani & Karlshøj	v		v						v		v			
2018	Chen, Liu, & Wu						v	v		v		v			v
2018	Dimyadi, Solihin, & Amor			v						v		v	v		
2018	Marzouk & Daoor				v	v				v		v		v	v
2018	Porto et al.		v						v		v		v		v
2019	Atyabi, Moghaddam, Rajabifard				v					v		v		v	v
2019	Cheng et al.				v			v		v		v			
2019	Fu & Liu				v				v				v		
2019	Mirahadi, McCabe, & Shahi				v					v		v			v
2019	Ronchi et al.				v				v	v			v		
2019	Roshanak	v			v		v	v		v					v
2019	Selin, Letonsaari, & Rossi				v					v		v	v		
2019	Shi, Dao, Jiang, & Pan			v						v		v	v	v	v
2019	Sun & Turkan			v	v					v		v	v		
2020	Bayat et al.				v					v		v			v
2020	Bina & Moghadas				v					v		v		v	v
2020	Chen, Lai, & Lin						v		v						v
2020	Guo et al.				v					v		v	v		
2020	Khan et al.	v	v		v	v			v		v				v
2020	Kincelova, Boton, Blanchet, & Dagenais	v	v						v		v				v
2020	Liu, Zhang, & Wang	v					v		v		v				v
2020	Lu, Yang, Xu, & Xiong							v		v		v			v
2020	Ma & Wu	v			v			v	v			v			v
2020	Mirahadi & McCabe			v	v			v		v		v	v	v	v
2020	Sun & Turkan			v	v			v		v		v		v	v
2021	Chen, Hou , Zhang, & Moon				v			v		v		v	v		
2021	Deng et al.				v			v				v	v		
2021	Diao & Guo			v	v					v		v	v		
2021	Lotfi, Behnam, & Peyman			v						v		v			v
2021	Mirahadi & McCabe	v			v			v		v		v			v
2021	Siddiqui et al.	v		v	v					v		v	v		

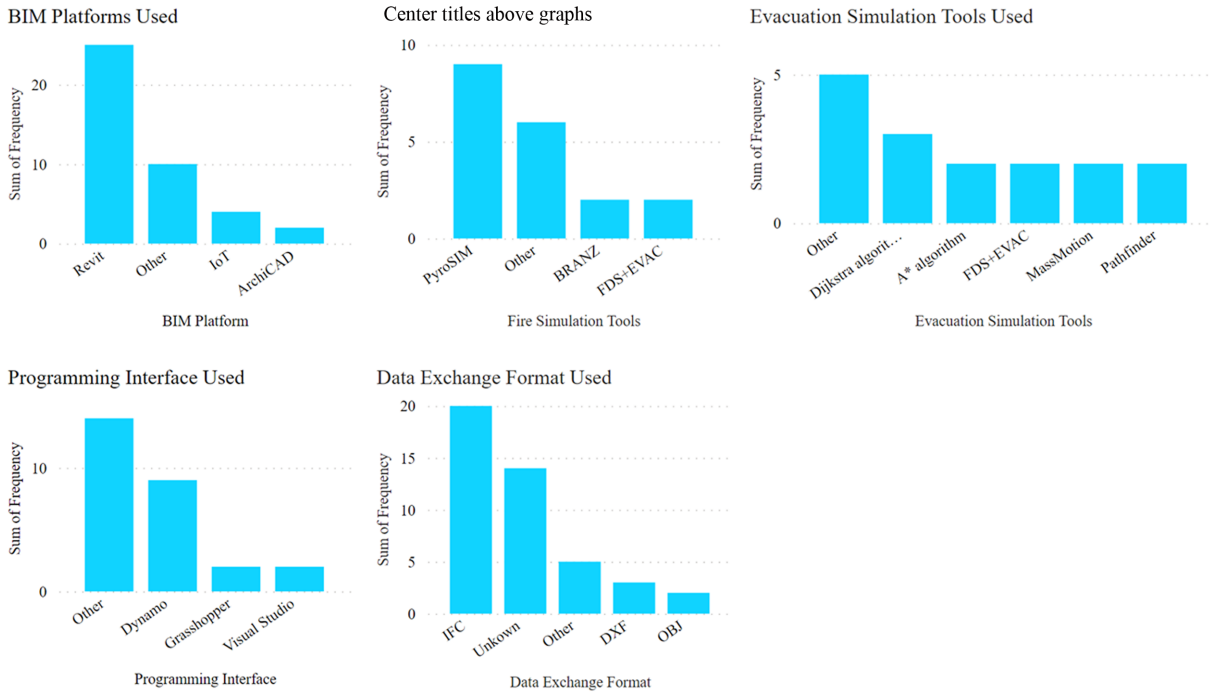


Figure 4. Technologies used for integrating fire safety with BIM.

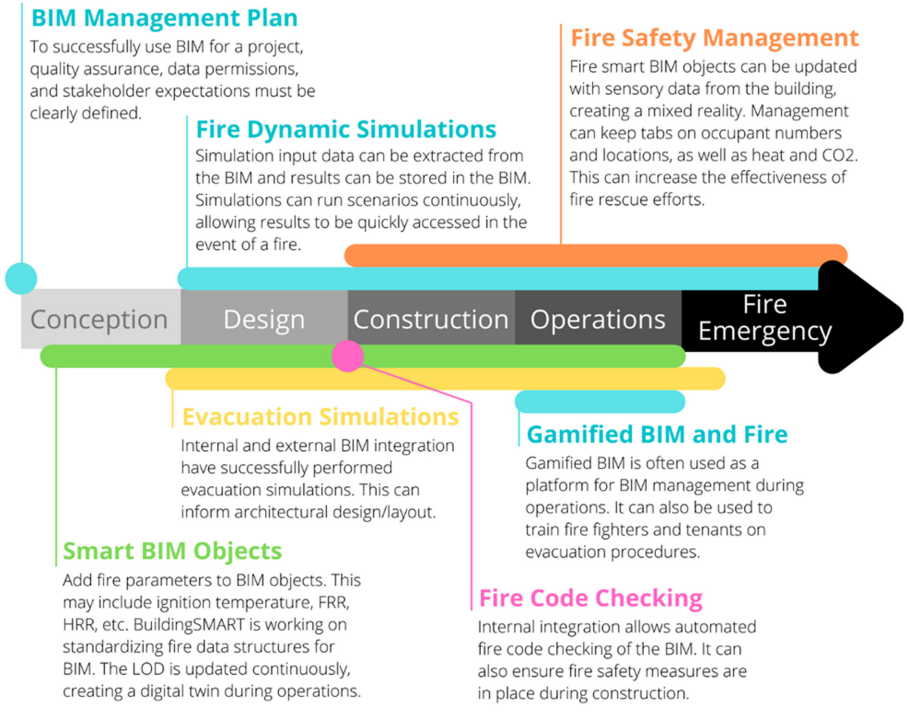


Figure 5. Roadmap to using BIM for fire safety engineering.

cost while too broad of an outline can increase risk of late identification of threats (Alfieri et al. 2020).

During the design phase, the LOD of a BIM object OR of BIM objects begins to be developed in stages, progressing as the design progresses. It is also during this phase that fire and evacuation simulations must be utilized to identify the worst fire scenarios and plan for occupant safety. Code-checking is also used during this design phase. If the number of penetrations within a FRR wall are exceeded during design, designers can be warned, ultimately preventing the wall from being compromised. A prescriptive approach can also be used for

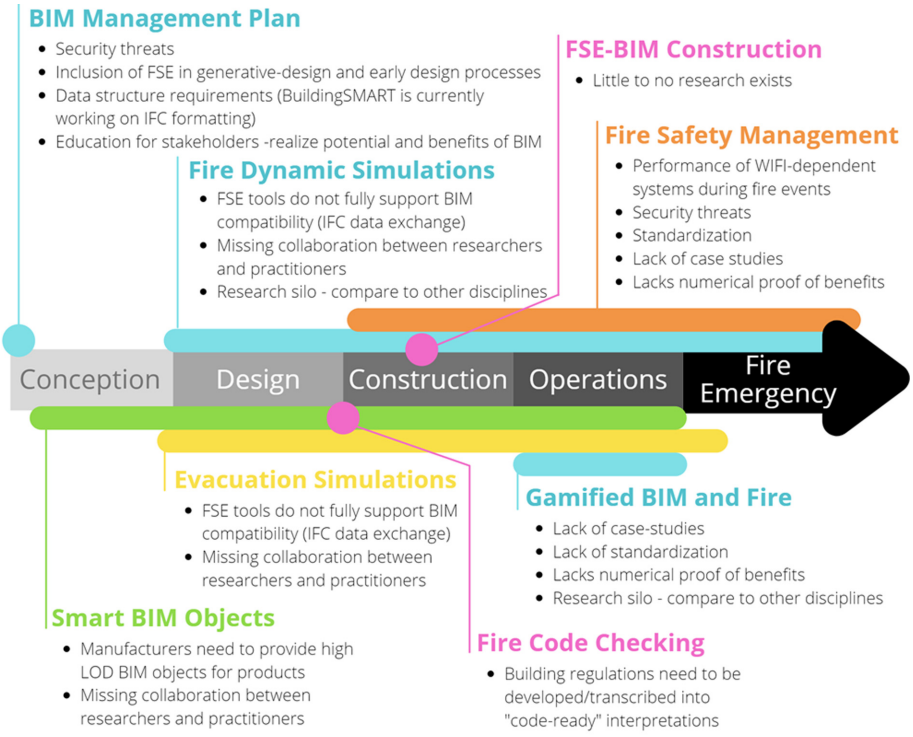


Figure 6. Future Research for FSE-BIM Integration.

evacuation design although this is less suitable for the complexity of modern tall buildings. By involving the FSE sector from the beginning of early design, FSE can be better integrated into the BIM and included in generative design practices. Ultimately, this would inform stakeholders on design solutions that better consider life safety into the overall design. During the design phase, fire safety during construction should be considered. This is an area of much needed further research with the authors having only found two papers (Marzouk and Daoor 2018, Khan et al. 2020) regarding this. Evacuations can be simulated for each construction phase, creating new updated evacuation plans. Fire extinguisher location and installation can also be managed. Many building fires are construction fires and evacuation times change throughout the project.

Construction management of fire safety relates closely with operations management. Operations tend to utilize more extended reality than other BIM applications. Researchers suggest gamified BIM to be used as a more intuitive platform for operation management. This provides a database which can augment real world devices with the virtual one, its digital twin. This allows for operations and maintenance to better identify fire fighting equipment, their state of repair, and status. It also provides a system for a fire risk analysis of the building and activities to be constantly evaluated in real time. If the occupancy changes, this will be identified and assessed automatically. This can significantly lower the risk of a fire scenario, however studies that prove this are limited since such systems are slow to be adopted in reality.

During a fire emergency, BIM can still positively influence the outcome of fire safety. The synchronous digital twin BIM can monitor sensor input for fires in hopes of identifying a fire sooner than a fire alarm would. To the authors knowledge, this is yet to be proven. Once the fire is identified and locations of occupants are known, optimized evacuation paths can be calculated and communicated to occupants by smart speakers, mobile devices, and/or ADDS. Live updates of the fire and evacuation scenario can be provided to the fire fighters reducing their exposed risk.

Overall, research efforts on fire-BIM integration are redundant silos of information. For example, fire dynamic simulation integration could learn from evacuation simulation integrations. It was found that more studies need to shift to real applications of integrating BIM with fire safety. This needs to involve more industry partners which are currently excluded from the technological developments. Fire involvement with BIM is behind other disciplines in industry. This would be improved with more involvement from industry partners. A lot more work needs to be done in interoperability for external integration purposes which is essential for performance-based design. Software developers will have the greatest impact and responsibility in this area. Another identified issue is data management. Permissions and quality assurance processes are essential for the integration to be effective and reliable. For complex buildings, the size of the BIM can be extremely large, calling need for cloud-

based storage which poses risk to security threats. The LOD of available BIM object libraries is currently not mature enough to supply fire and smoke simulations with enough information. This development task will be greatly influenced by the manufacturing industry where demand for product digital twins is on the rise. Figure 6 below summarizes these current issues with the state-of-the-art BIM and FSE integration which require further research and development.

This literary assessment of integrating BIM with fire safety has limitations to its context. The literature analysis is limited in the following ways: (1) The sample selection is subject to personal biases since they were not statistically randomly chosen. (2) Some BIM integration categories have a significantly limited sample size. (3) Sample was limited to English language papers.

5. Conclusions

Fire safety engineering can utilize Building Information Modelling (BIM) throughout a building's life by participating in the Level of Development (LOD) of smart BIM objects, automated fire code checking, prescriptive fire protection design, data exchange to evacuation and fire simulations, fire safety planning during construction, fire safety management during operations, and fire emergency management. Research in these developing applications have indicated the benefit in reducing fire risk but fire code checking is the only application that has shown cost benefits. Adoption of BIM in fire safety engineering is slow and behind other disciplines which may be improved if research involved more industry partners, as only 8 out of the 49 BIM-Fire papers reviewed involved industry partners. The most commonly used BIM platform, fire simulation tool, programming interface, and data exchange format used in research are Revit, PyroSim, Dynamo, and IFC respectively. Research does not show a preference for a particular brand of evacuation simulation tool. This information may help practitioners when choosing more compatible software for their fire design integration with BIM. The research has gravitated towards integrating prescriptive building codes within the BIM using API for construction operations and checking fire code compliance during design and operations. Performance-based fire design tends to use external BIM integration by exchanging data between the BIM and simulation tool, usually in IFC format. Emerging technologies such as gamified BIM are progressing capabilities of smart buildings and allowing for fire risk mitigation. This is all technology and information that should be defined at the beginning of a project when the BIM management plan is specified between disciplines. It is essential that the fire safety engineer be involved from the beginning to make clear their needs and be informed on the building's design objectives. It is during this stage that technology, software, and data need to be defined from the fire safety perspective. The roadmap provided by the authors in this paper offer holistic guidance for making such decisions. For BIM technology to reach its potential, industry manufacturers need to provide high LOD fire BIM objects, fire engineers and researchers need to collaborate, software developers need to improve interoperability (the use of standardized file exchange formats - IFC), and building owners and management need to be educated on how use the benefits provided. In the future, it is possible that the digital twin of a large data sample of buildings will be able to collect big data on human and fire behaviour during real events. This will better inform design practices and base assumptions, ultimately improving the life safety of high-rise buildings. Additionally, FSE would be fully integrated into the BIM collaborative process with other building stakeholders from early design phases, allowing for inclusion in other BIM tools such as generative design. This would ultimately result in an optimized design that truly considers life safety.

Acknowledgments

The authors would like to acknowledge Bronwyn Chorlton, Chloe Jeanneret, and Tim Young of York University for their assistance. This research has been funded by the Natural Sciences and Engineering Research Council of Canada and the Canada Graduate Scholarships - Master's program.

References

Alfieri, E., Seghezzi, E., Sauchelli, M., Giuda, G. M., and Masera, G. (2020). "A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study." Architectural Engineering and Design Management, *16*(4), 247-269.

Alizadehsalehia, S., Hadavib, A., and Huangc, J. C. (2020). "From BIM to extended reality in AEC industry." Automation in Construction, 2020(116), 103254.

Amaro, G., Raimondo, A., Ebra, D., and Ugliotti, F. M. (2017). "A BIM-Based Approach Supporting Fire Engineering." IFireSS 2017 2nd International Fire Safety Symposium (pp. 137-144). Naples: Doppiavoce di P.Trautteur.

Andrews, C. (2020, February 1). "Gamification in GIS and AEC." Retrieved from esri: https://www.esri.com/arcgis-blog/products/arcgis/3d-gis/gamification-in-gis-and-aec/

Atyabi, S., Moghaddam, M. K., and Rajabifard, A. (2019). "Optimization of Emergency Evacuation in Fire Building by Integrated BIM and GIS." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 131-139.

Banfi, F., Brumana, R., and Stanga, C. (2020). "Extended reality and informative models for the architectural heritage: from scan-to-BIM process to virtual and augmented reality." Virtual Archaeology Review, 10(21), 14-30.

Bayat, H., Delavar, M. R., Barghi, W., EslamiNezhad, S., Hanachi, P., and Zlatanova, S. (2020). "Modeling of

Emergency Evacuation in Building Fire." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, *XLIII-B4-2020*(XXIV), 321-327.

Beltrani, L., Giuliani, L., and Karlshøj, J. (2018). "Fast track BIM integration for structural fire design of steel elements." eWork and eBusiness in Architecture, Engineering and Construction, 43-50.

Bina, K., and Moghadas, N. (2020). "BIM-ABM simulation for emergency evacuation from conference hall, considering gender segregation and architectural design." Architectural Engineering and Design Management.

BSI, Department for Business, Energy, and Industrial Strategy. (2016). "About BIM Level 2." Retrieved February 18, 2020, from https://bim-level2.org/en/about/

buildingSMART. (2021). "Fire Safety Engineering & Occupant Movement openBIM Standards." Retrieved from Building SMART International: https://www.buildingsmart.org/standards/calls-for-participation/fire-safety/

BuildingSMART. (2021, May). "IFC4 Software Certification Delivers First Milestone." Retrieved February 18, 2020, from buildingSMART International: https://buildingsmart-canada.ca/ifc4-software-certification-delivers-first-milestone/

Campbell, R. (2020). "Fires in Structures under Construction or Renovation." National Fire Protection Association (NFPA).

Chen, H., Hou, L., Zhang, G., and Moon, S. (2021). "Development of BIM, IoT and AR/VR technologies for fire safety and upskilling." Automation in Construction, 2021(125), 103631.

Chen, X., Liu, C., and Wu, I. (2018). "A BIM-based visualization and warning system for fire rescue." Advanced Engineering Informatics, 2018(37), 42-53.

Chen, Y., Lai, Y., and Lin, Y. (2020). "BIM-based augmented reality inspection and maintenance of fire safety equipment." Automation in Construction, 2020(110), 103041.

Cheng, J. C., Tan, Y., Song, Y., Mei, Z., Gan, V. J., and Wang, X. (2019). "Developing an evacuation evaluation model for offshore oil and gas platforms using BIM and agent-based model." Automation in Construction, *2019*(89), 214-224.

Choi, J., Choi, J., and Kim, I. (2014). "Development of BIM-based evacuation regulation checking system for high-rise and complex building." Automation in Construction(46), 38-49.

Deng, H., Ou, Z., Zhang, G., Deng, Y., and Tian, M. (2021). "BIM and Computer Vision-Based Framework for Fire Emergency Evacuation Considering Local Safety Performance." Sensors, 2021(21), 3851.

Diao, Y., and Guo, Z. (2021). "Fire emergency evacuation model of light rail station based on BIM technology." Journal of Physics: Conference Series, 2021(1903), 012035.

Dimyadi, J., Solihin, W., and Amor, R. (2018). "Using IFC to Support Enclosure Fire Dynamics Simulation." EG-ICE, 339-360.

Eftekharirad, R. (2019, April). "Improving Fire Emergency Management Using Occupant Information and BIM-Based Simulation." Montreal, Quebec, Canada: Concordia University.

Eleftheriadis, S., Mumovic, D., Greening, P., and Chronis, A. (2015). "BIM Enabled Optimisation Framework for Environmentally Responsible and Structurally Efficient Design Systems." 32nd International Symposium on Automation and Robotics in Construction and Mining (pp. 708-716). Bratislava: International Association for Automation & Robotics in Construction (IAARC).

Fu, M., and Liu, R. (2019). "Automatic Generation of Path Networks for Evacuation Using Building Information Modeling." Computing in Civil Engineering, 320-327.

Gao, Y., and Xue, H. (2017). "Design and Simulation of Building Fire Protection System Based on BIM Technology." 29th Chinese Control and Decision Conference (pp. 2729-2732). Chongqing: Northeastern University of China.

Georgiadou, M. C. (2019). "An overview of benefits and challenges of building information modelling (BIM) adoption in UK residential projects." Construction Innovation, 19(3), 298-320.

Ghalenoei, N. K., Saghatforoush, E., and Rezvanian, A. (2020). "The Use of Building Information Modelling in Fire Safety Engineering." First International Conference on Management, Ethic and Business. Shiraz: Management, Ethic, Business.

Guo, Y., Zhu, J., Wang, Y., Chai, J., Li, W., Fu, L., Gong, Y. (2020). "A Virtual Reality Simulation Method for Crowd Evacuation in a Multiexit Indoor Fire Environment." International Journal of Geo-Information, 2020(9), 750.

Johnston, A. (2021). "The Evolving Adaption of Building Information Modelling." Fire Protection Engineering Magazine(89), pp. 16-23.

Khan, N., Ali, A. K., Tran, S. V., Lee, D., and Park, C. (2020). "Visual Language-Aided Construction Fire Safety Planning Approach in Building Information Modeling." Applied Sciences, 2020(10), 1704.

Kincelova, K., Boton, C., Blanchet, P., and Dagenais, C. (2019). "BIM-Based Code Compliance Checking For Fire Safety in Timber Buildings: A Comparison of Existing Tools." CSCE Annual Conference (p.226). Laval: Canadian Society for Civil Engineering.

Kincelova, K., Boton, C., Blanchet, P., and Dagenais, C. (2020). "Fire Safety in Tall Timber Building: A BIM-Based Automated Code-Checking Approach." MDPI Buildings Journal, 121.

Liu, Z., Zhang, A., & Wang, W. (2020). "A Framework for an Indoor Safety Management System Based on Digital Twin." Sensors, 2020(20), 5771.

Lotfi, N., Behnam, B., and Peyman, F. (2021). "A BIM-based framework for evacuation assessment of high-rise buildings under post-earthquake fires." Journal of Building Engineering, 2021(43), 102559.

Lovreglio, R., Thompson, P., and Feng, Z. (2021, June). "Letter to the Editor: Automation in Fire Safety Engineering using BIM and Generative Design." Fire Technology. Research Gate.

Lu, X., Yang, Z., Xu, Z., and Xiong, C. (2020). "Scenario simulation of indoor post earthquake fire rescue based on building information model and virtual reality." Advances in Engineering Software(143), 102792.

Ma, G., and Wu, Z. (2020). "BIM-based building fire emergency management: Combining building users' behavior decisions." Automation in Construction, 2020(109), 102975.

Marzouk, M., and Daoor, I. A. (2018). "Simulation of labor evacuation: The case of housing construction projects." HBRC Journal, 2018(14), 198-206.

Menendez, J., Hairstans, R., Leitch, K., and Turnbull, D. (2012). "A Structural Engineering Platform for Timber Modern Methods of Construction."

Mirahadi, F., and McCabe, B. (2020). "Evacusafe: Building Evacuation Strategy Selection Using Route Risk Index." Journal of Computing in Civil Engineering, 2(34), 04019051.

Mirahadi, F., and McCabe, B. Y. (2021). "EvacuSafe: A real-time model for building evacuation based on Dijkstra's algorithm." Journal of Building Engineering, 2021(34), 101687.

Mirahadi, F., McCabe, B., and Shahi, A. (2019). "IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling." Automation in Construction(101), 1-16.

Moussaid, M., Helbing, D., and Theraulaz, G. (2011, April 26). "How simple rules determine pedestrian behaviour and crowd disasters." PNAS, pp. 6884-6888.

Ozturk, G. B., and Eraslan, O. (2019). "Identifying the Advantages of BIM in Structural Design." Eurasian Journal of Civil Engineering and Architecture, 25-32.

Patlakas, P., Livingstone, A., and Hairstans, R. (2015). "A BIM Platform for Offsite Timber Construction." Education and research in computer aided architectural design in Europe (eCAADe). 1, pp. 597-604. Vienna: Education and research in computer aided architectural design in Europe (eCAADe).

Porto, M., Franco, J., Correa, L., Alves, L., and Baracho, R. (2018). "BIM as a Structural Safety Study Tool in Case of Fire - BIMSCIP." Systemics, Cybernetics and Informatics, *16*(1), 81-86.

Potatacas, J., Dawood, N., and Kassem, M. (2014). "Evaluation of IFC and COBIE as data sources for asset register creation and service life planning." 14th Internation Conference on Construction Applications of Virtual Reality. Sharjah.

Public Works and Government Services Canada. (2015, September 22). "Building Information Modeling (BIM) - Centre Block (EP748-160056/001/FK)." Retrieved February 18, 2020, from https://buyandsell.gc.ca/procurement-data/award-notice/PW-FK-289-67842-001

Pybus, C., Graham, K., Doherty, J., Arellano, N., and Fai, S. (2019). "New Realities for Canada's Parliament: A Workflow for Preparing Heritage BIM for Game Engines and Virtual Reality." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 945-952.

Quiquero, H., Smith, M., and Gales, J. (2018). "Developing Fire safety Engineering as a Practice in Canada." Canadian Journal of Civil Engineering, 527-536.

Ralph, B., and Carvel, R. (2018). "Coupled Hybrid Modelling in Fire Safety Engineering; a Literature Review." Fire Safety Journal, 100, 157-170.

Ren, R., and Zhang, J. (2019). "Model Information Checking to Support Interoperable BIM Usage in Structural Analysis." Computing in Civil Engineering, 361-368.

Ren, R., and Zhang, J. (2021). "A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions." Advances in Civil Engineering, 8824613.

Ronchi, E., Corbetta, A., Galea, E., Kinateder, M., Kuligowski, E., McGrath, D., Toschi, F. (2019). "New approaches to evacuation modelling for fire safety engineering applications." Fire Safety Journal(106), 197-209.

Ruppel, U., and Schatz, K. (2011). "Designing a BIM-based serious game for fire safety evacuation simulations." Advanced Engineering Informatics, 2011(25), 600-611.

Ruppel, U., Zwinger, U., Kreger, M., and Scatz, K. (2017). "Research with BIM for Fire Protection." TRUTZ International, 2017(1), 8-13.

Selin, J., Letonsaari, M., and Rossi, M. (2019). "Emergency exit planning and simulation environment using gamification, artificial intelligence and data analytics." Procedia Computer Science, 2019(156), 283-291.

Shi, J., Dao, J., Jiang, L., and Pan, Z. (2019). "Research on IFC- and FDS-Based Information Sharing for Building Fire Safety Analysis." Hindawi Advances in Civil Engineering, 2019, 3604369.

Shino, G. K. (2013, April 3). "BIM and Fire Protection Engineering." Consulting-Specifying Engineer Magazine, pp. 34-31.

Siddiqui, A. A., Ewer, J. A., Lawrence, P. J., Galea, E. R., and Frost, I. R. ((In Press)). "Building Information Modelling for performance-based Fire Safety Engineering analysis - a strategy for data sharing." Journal of Building Engineering, 102794.

Smith, M., and Gales, J. (2016, Fall). Integrating Fire as a Load Case with BIM. *Advantage Steel*, pp. 32-38.

Smith, M., and Teravainen, A. (2018, February). "Evolving the Fire Design Process through BIM." Innovation Spotlight, pp. 14-18.

Spearpoint, M. J., and Dimyadi, J. A. (2007). "Sharing Fire Engineering Simulation Data Using IFC Building Information Model." International Congress on Modelling and Simulation. Christchurch.

Staub-French, S., Poirier, E. A., Calderon, F., Chikhi, I., Zadeh, P., Chudasma, D., and Huang, S. (2018). "Building Information Modeling (BIM) and Design for Manufacturing and Assembly (DfMA) for Mass Timber Construction." Vancouver: University of Brittish Columbia.

Sun, Q., and Turkan, Y. (2019). "A BIM Based Simulation Framework for Fire Evacuation Planning." Advances in Informatics and Computing in Civil Engineering, 431-438.

Sun, Q., and Turkan, Y. (2020). "A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance." Advanced Engineering Informatics, 2020(44), 101093.

Vilutiene, T., Kalibatiene, D., Hosseini, M. R., Pellicer, E., & Zavadskas, E. K. (2019). "Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature." Hindawi Advances in Civil Engineering, 5290690.

Wang, S., Wang, W., Wang, K., and Shih, S. (2015). "Applying Building Information Modeling to Support Fire Safety Management." Automation in Construction, *2015*(59), 158-167.

Wu, J., and Zhang, J. (2019). "New Automated BIM Object Classification Method to Support BIM Interoperability." Journal of Computing in Civil Engineering, 361-368.