Fire Technology, 58, 3317–3351, 2022

Manufactured in The United States
https://doi.org/10.1007/s10694-022-01313-3

The Digital Transformation in Fire Safety Engineering over the Past Decade Through Building Information Modelling: A Review

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Received: 1 November 2021/**Accepted:** 11 August 2022/**Published online:** 23 September 2022

Abstract. Building information modelling (BIM) is widely considered to be leading the digital transformation of the AEC industry because of its data management capabilities among different stakeholders and across the building life-cycle. Fire safety engineering (FSE) is one of the disciplines that has been excluded for a long time from integrated approaches such as BIM, even though ensuring fire safety is a fundamental aspect of building performance. This paper presents a systematic literature review of BIM–FSE integration methodologies to highlight its potentialities for building life-cycle management and the digital transformation of the AEC domain. The findings show that the majority of BIM–FSE applications are focused on fire and evacuation simulations, followed by detection, monitoring and real-time emergency management. Technologies that are often involved in BIM-based fire safety solutions are CFD-based technologies, game- augmented and virtual reality, and the internet of things. Native formats are the most used for data sharing, while open standards still lack adequate data structures for FSE applications. The review highlights the benefits, embedded potentialities and limitations of the BIM–FSE integration in a decade of research studies. Future research directions for the digital transformation of FSE through BIM are proposed in a research agenda.

Keywords: Building information modelling, Fire safety engineering, BIM, FSE

Abbreviations

AEC	Architecture, engineering and construction
BIM	Building information modelling
IFC	Industry foundation classes
MVD	Model view definition
FSE	Fire safety engineering
HVAC	Heating, ventilation, air conditioning
FDS	Fire dynamics simulator
CFD	Computational fluid dynamics

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GIS	Geographical information system
ABM	Agent based modelling
IoT	Internet of Things
AVR	Augmented and virtual reality
MEP	Mechanical, electrical, plumbing
VR	Virtual reality
BPMN	Business process modelling and notation
FM	Facility management

1. Introduction

The importance of adequate fire safety measures becomes evident when a localised fire propagates, causing economic losses and loss of life, as happened in some of the deadliest fires in recent history [1, 2]. Other major consequences are related to the detrimental effects of a harmful air quality level on the occupants' health. Even fires that did not result in any loss of life can be considered a disaster for society. This was the case of the 850-year-old icon of European History, Notre Dame Cathedral, damaged in 2019 [3]. The Grenfell tower accident (June 2017) [4] and the tall building façade fire of Milan (August 2021) [5] point towards a lack of information dissemination among stakeholders responsible for ensuring the fire safety of a building.

The digital transformation of the architecture, engineering and construction (AEC) sector provides a promising perspective to better manage fire safety related issues. Even though the AEC sector generates approximately $ 10 trillion in annual revenue (about 6% of global gross domestic product), it still struggles to match the productivity levels of other industries [6]. The digitalisation of this sector is projected to increase savings by up to 20% ($1.7 trillion) annually [7, 8].

Building information modelling (BIM) is widely considered as the methodology that can make the digitalisation of the construction sector possible. BIM allows the digital creation of an accurate virtual model of a building, facilitating an integrated design and construction process that improves the project quality, saving costs and time [9]. The acronym BIM refers to an informative digital model that virtually represents the three-dimensional geometry of the building components, non-physical objects (spaces and zones) and connects them in a hierarchical project structure. One of the main features of a building information model is the semantic enrichment of geometric objects (component type, materials, technical properties, costs) including the relationships between the components and other physical or logical entities [10]. Mainly, it is a shared information repository for collaboration throughout the facility's life cycle [11] and serves as a reliable basis for decisions [12].

Abanda et al. [13] carried out a critical analysis of BIM systems used in construction projects in 2015 and identified 122 major BIM software applications and 71 plug-ins. According to the authors, data file formats play a crucial role in the information exchange process because they facilitate the importing and/or exporting into/from other software systems. In general, information exchange in a BIM environment takes place through:

- native file formats, restricted to a particular type of software;
- open exchange file formats such as the IFC (industry foundation classes), used to exchange data between any software that can process IFC based data;
- formats for specialised applications such as green building extensible markup language (gbXML) used for energy analysis;
- plug-in (or add-in or add-on), a component that adds features to existing applications.

The international organisation BuildingSMART, an association formed of more than 800 members (organisations, companies and institutes), plays a major role in promoting the digital transformation of the AEC industry and its technical core is based around the IFC. IFC is an open, vendor-neutral international standard which was incorporated in ISO Standard 16739 in 2013; speeding up the adoption process in different countries. IFC can represent geometric and semantic features of the building using an object-oriented approach. It is a powerful albeit complex data model that allows the user to describe a building exhaustively, but this requires effort from software vendors to guarantee compatibility with the IFC standard. Some software applications used for specific studies such as energy or structural analysis may not need the huge quantity of data that IFC provides.

For this reason, the concept of model view definition (MVD) was introduced by BuildingSMART. An MVD is a subset of the IFC schema that specifies which part of the IFC must be implemented according to the specific information exchange requirements. A list of the BuildingSMART international official MVDs releases is published on the association's technical website [14]. Despite problems related to the complexity of the data model, the IFC data format plays a key role in the path towards interoperability. Although the AEC industry spends billions each year to solve interoperability issues between systems, the management of all the phases and aspects of the building life-cycle has not been covered yet [15–18]. Currently, the occupant movement analysis MVD project covering circulation and evacuation modelling aspects is underway at BuildingSMART [19] while a new call for participation to develop an MVD to cover fire modelling aspects has recently been published [20]. This represents a turning point for FSE, which has been a slow adopter of the digital developments in the AEC industry.

The general objectives of FSE are life safety and the protection of property and the environment, as stated in the ISO 23932-1:2018 standard [21]. These objectives can be achieved by applying prescriptive or performance-based methods. The former relies on rules established by a legislator, and fire safety objectives are considered satisfied a priori if the project is compliant with these rules. This method has been the most used in the past [22]. The latter requires a deep knowledge of fire science in order to provide solutions that guarantee certain performance levels for the project [23].

The use of FSE methods and BIM applications is encouraged by international organisations, standards and regulations, and life safety is a concern to citizens and governments [7, 24–28], but BIM-based FSE applications in common practice are still few. In the ISO 23932-1 standard [21], a flow chart illustrates the fire safety engineering design process. Figure 1 shows the type of data that the BIM

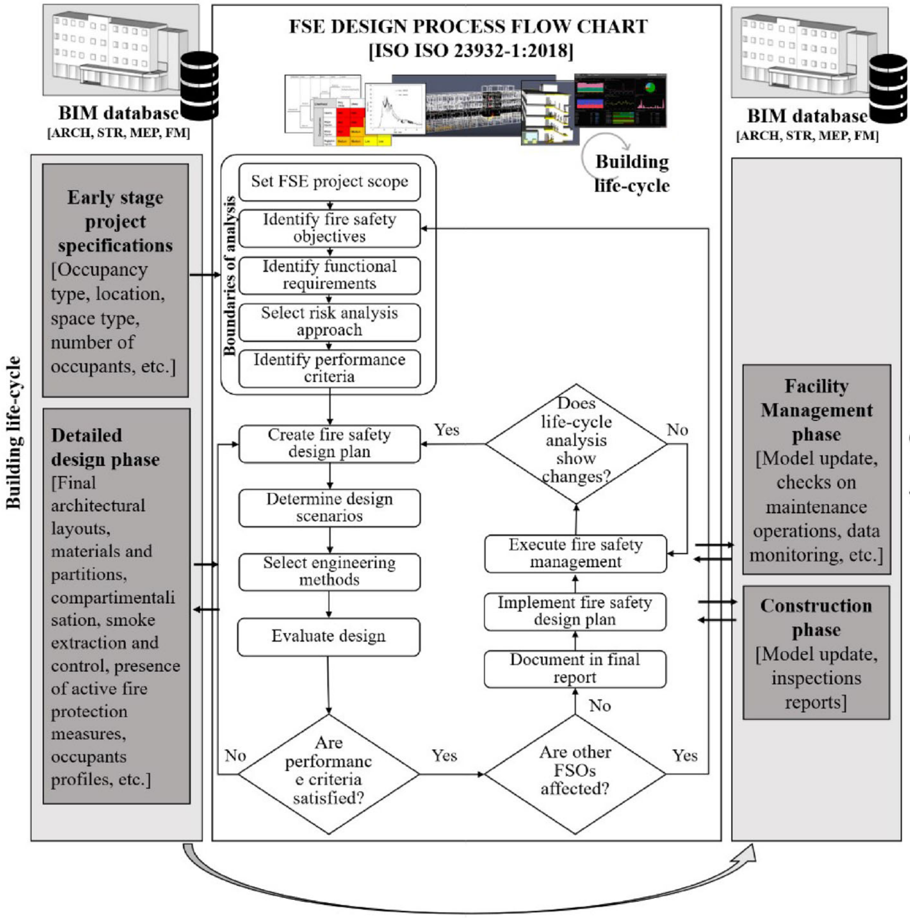

Figure 1. Flow chart illustrating the fire safety engineering design process [21] and type of information to be retrieved by the BIM database along the building life-cycle.

database can provide to the fire engineer for his/her activities according to the ISO 23932 flowchart and building life-cycle phases.

The need for the integration of BIM and FSE was formally stated in 2011 by the Society of Fire Protection Engineers (SFPE), although papers on the issue were published in the previous years. The SFPE declared that, although FSE has not been a priority for BIM software and tools development, the evolution of BIM technology provides new opportunities for the fire protection engineering community to become involved in the process by influencing the integration of the FSE discipline into BIM applications [29]. It highlighted fire suppression systems design, fire alarm and notification systems design, life safety and code compliance, and performance-based design as aspects that could be addressed using BIM.

After 9 years, in an article published in the SFPE magazine [30], it is recognised that the incorporation of FSE into BIM has been "hesitant" and big changes are expected in the coming decade due to initiatives undertaken for the achievement of standardization within digital fire safety.

In recent years, when fire protection was considered in a BIM process, it was usually managed as an installation discipline (such as electricity, plumbing or heating, ventilation and air conditioning (HVAC)) [31]. Major effort has been expended on exporting building information models for fire simulations, but the complexity of integration, high costs [23] and the significant differences between software applications made many projects difficult to implement. In 2008, Dimyadi et al. [32] published their work on a fire engineering IFC model parser but the data mapping implementation was limited to basic building geometry. The Project Scorch focused on including the fire dynamics simulator (FDS) software [33] in the Revit BIM tool [34], but it was abandoned before the development of a commercial product [35]. Different data-exchange options between BIM software and computational fluid dynamics (CFD) simulation tools were investigated, for both vendor-neutral formats and proprietary formats, but manual editing was still required [36]. In a technical report by Briab [37], critical factors for the BIM–FSE integration were identified based on in-depth interviews with various actors in the building industry. The authors underlined the lack of knowledge about BIM in the fire consultancy sector and the need for: standardisation of concepts and processes; clearer definition of roles and responsibilities; fire regulations that make the development of executable code for compliance checking easier; an IFC MVD [38] for fire protection to have a program-neutral data exchange format.

An important step towards the integration of the fire safety discipline into the digital transformation process is the Hackitt report [39], which describes the results of the building regulations and fire safety review carried out after the Grenfell Tower fire. It underlines the need for a golden thread of information for fire safety in buildings, to achieve accountability, transparency, and improved communication of fire safety. These targets are also mentioned in the BuildingSMART call for the development of an MVD for fire safety [20].

Currently, a comprehensive overview of the integration between the BIM and FSE disciplines is missing and no studies focusing on the benefits and limitations of such an integration have been found in the literature. This paper presents a systematic literature review on the state-of-the-art research related to the integration between BIM and FSE in the past 10 years. The aim of the review is to report and discuss findings from studies where the BIM approach and tools have been used to support FSE and its digital transformation process. The study attempts to answer the following research questions:

– How can FSE benefit from BIM integration?
– What are the main limitations that need to be overcome to fulfil the potential of BIM–FSE integration?
– What could be the future research directions for such integration?

The paper is divided into five sections. After the introduction, the adopted systematic literature review methodology is described. In the third section, results are classified according to the application domains and supporting technologies. The benefits and current limitations of BIM–FSE integration are discussed in the fourth section and suggestions for possible future research directions follow.

2. The Systematic Review: Method

Systematic reviews have been described as the gold standard among literature reviews because they allow the researcher to synthesise research findings in a systematic, transparent, and reproducible way [40]. The aim of this kind of review is to answer specific research questions by applying explicit, systematic methods to reduce bias [41–43]. In this work, the systematic literature review was carried out according to the five-step approach proposed by Khan et al. [44] (Figure 2).

Step 1: *Framing questions for the review*—The research topics to be addressed by the review were specified in the form of clear and structured questions before beginning the review work.

Step 2: *Identifying relevant work*—The search criteria for the literature were established. The search refers to papers published in English from 2010 to 2020, considering that both the investigated topics have become a research subject recently. The set of keyword combinations involving BIM and FSE were identified and used to search the two major and most comprehensive sources of publications, namely the "Web of Science (WoS)" and "Scopus" online databases [45, 46], for academic and applied publications related to these topics. The identified keyword combinations described in Table 1 were searched for in the title, abstract

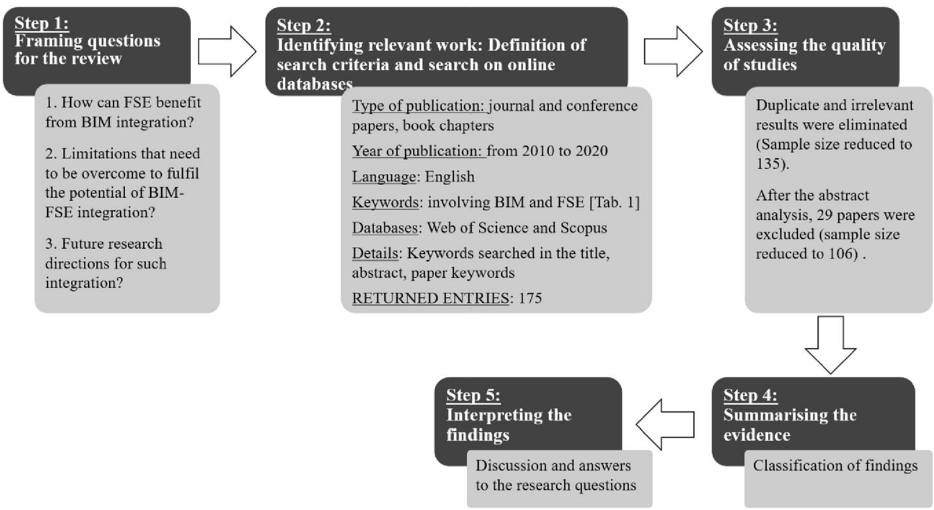

Figure 2. An illustration of the research steps followed during the systematic literature review.

Table 1
The Keyword Combinations Used for the Parsing Through the Literature Databases

Keyword 1	AND	Keyword 2
Building Information Modelling OR BIM		Fire Safety Engineering OR FSE OR Fire

and keywords, as usually done by scholars carrying out systematic literature reviews [47–49]. The research includes journal and conference papers as well as book chapters. The combinations included extended and acronym forms of BIM and FSE. The keywords such as "fire protection engineering" or "fire analysis" yielded a small number of results. Hence, a general combination of keywords referring to BIM and fire was used and this resulted in the most consistent sample of publications.

Step 3: *Assessing the quality of studies*—The body of work was narrowed down. Firstly, duplicate and irrelevant results were eliminated from the identified sample. Papers that were not available on the internet (e.g. inaccessible conference proceedings); articles from trade journals as well as multiple database entries of the same paper were excluded, 42 papers in total. Secondly, the abstracts of the articles were analysed to select articles that address the scope of the review. In particular, 29 papers were considered not to be pertinent to the literature review for one of the following reasons: (i) fire safety or BIM aspects were mentioned but not analysed in detail; (ii) fire safety and BIM were investigated separately; (iii) the BIM–FSE integration was mentioned in terms of future research. This reduced the sample size to 106 papers.

Step 4: *Summarising the evidence*—As BIM–FSE applications cover different aspects separately, the papers were grouped into application domains according to the fire safety issues investigated. The application domains were further divided into categories based on the technology employed. Moreover, selected scientific papers were used to show the main trends in BIM–FSE integration according to the year of publication, information exchange formats, BIM tools employed and BIM dimensions. This categorisation is discussed further in the following sections.

Step 5: *Interpreting the findings*—The results from the literature review are discussed and the answers to the research questions are provided based on the literature review.

3. Results

3.1. Application Domains for the BIM–FSE Integration

The research activities focusing on the BIM–FSE integration addressed various fire safety issues and building life-cycle phases. In order to highlight the main domains of application, the authors propose a categorisation of the reviewed papers into seven domains based on the research content.

(1) Fire safety design;
(2) Fire and evacuation simulations;
(3) Code and model checking;
(4) Detection, monitoring and emergency management;
(5) Investigation of causes of fire;
(6) Fire safety equipment modelling and maintenance;
(7) Education and training.

Some papers dealt with multiple application domains and are included in more than one domain. As BIM-based technology does not always cover all the needs of FSE applications, other technologies were required to address the research goals. Figure 3 gives an overview of technologies that were integrated with BIM according to the identified application domains. The classification is meant to improve the understanding of the state-of-the-art of BIM–FSE integration and to guide the discussion on the benefits and limitations of BIM–FSE integration. Furthermore, it also helps in answering the research questions of the literature review.

3.1.1. Fire Safety Design In this paper, the domain "Fire safety design" is related to several aspects of the design process and the nine articles grouped under this domain propose methodological or technological solutions needed to perform specific analyses, using BIM tools.

The most addressed topic within fire safety design is the design of fire emergency plans based on fire regulations [50–55]. However, in all these cases, the

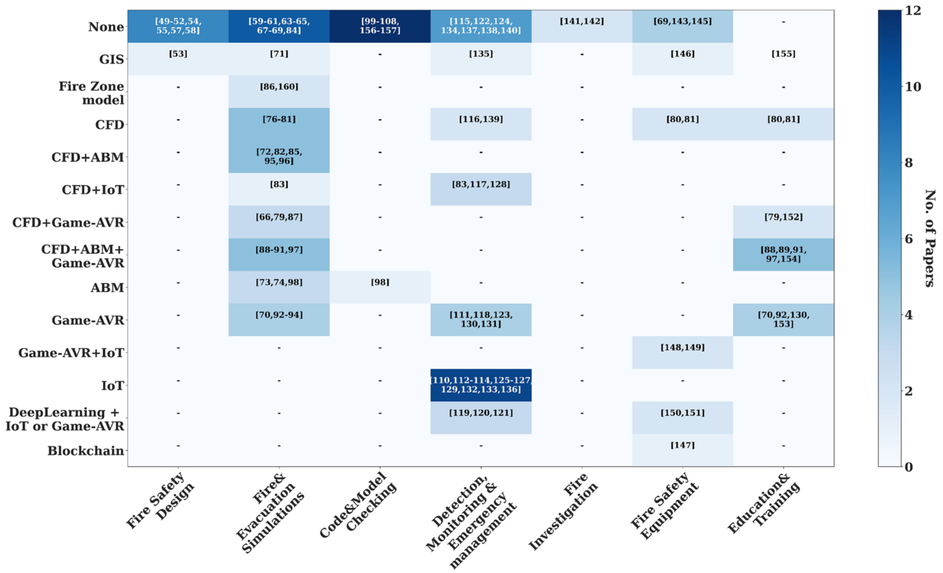

Figure 3. An overview of the fire safety engineering application domains that received the most research focus for the BIM–FSE integration.

design of evacuation plans was always verified for a given building geometry and BIM. The integration of the fire safety strategy starting from the concept phase, when early stage project specifications are given, is not attempted in any of the papers.

Stančík et al. [50] proposed a solution to automatically create the graphical portion of the building fire evacuation plan from the BIM model, by adjusting the floor plans graphics. Bi et al. [51] published their study about a modular management platform for fire emergency plans in which three modules were based on data retrieved from BIM technology: building outline, fire equipment information, and fire simulator and response. This demonstrates that the fire engineer needs different types of data (building geometry and floor layout, fire equipment, occupants profile) to ensure fire safety. In Wu et al.'s work [53], the network analysis for the calculation of the shortest evacuation path in BIM models was integrated with risk analysis. A probability related to the start location of fatal fire is assigned to each building space according to its occupancy. The risk index associated with a specific room is given by the sum of the fatal fire frequency of all the other rooms that are along the exit route. Papers published by Wu and Zhang [54] and Kim et al. [55] focused on the representation of indoor building circulation and the data retrieved from BIM models included virtual space boundaries, space boundaries, door objects and vertical access objects.

The fire safety of structures was addressed by Beltrani et al. [56], who developed a Dynamo [57] script to export steel element sections from a BIM software application to a structural fire design software, and to import them back after analysis and eventual modification. Feng and Lin [58] worked on smoothing the development of the constructive MEP (mechanical, electrical and plumbing) BIM model. The information requirements for the model were identified by reviewing the construction specifications and collecting information from fire-fighting professionals. Ontology rules were developed based on these requirements to create a semantically rich MEP BIM model.

A fire risk assessment framework for different building categories was proposed by Zhang [59] and this is based on weighting factors established through a survey submitted to experts specialised in assessment. The framework allows the user to obtain an assessment score through the set algorithm by extracting the fire data of the building from the BIM, such as the water supply system of the indoor fire hydrant, fireproof door, firewall, fire resistance rating, fire compartment, fire separation, ventilation and smoke control and exhaust system, etc.

The reviewed papers showed that BIM research in the fire safety field is still emerging and some articles do not provide information about how the integration with BIM is realised. In general, when a use case is provided to demonstrate the effectiveness of a proposed framework, it is limited to just a few testing scenarios [52, 54, 56, 58]. The generalisation of solutions and their wider applicability remains unexplored.

3.1.2. Fire and Evacuation Simulations Fire and evacuation simulations are the application domain that comprises the majority of the reviewed papers, as shown in Figure 3. This domain contains studies that adopt different mathematical models, and consequently different technologies to simulate the fire dynamics, the building occupants' route (and eventually their behaviour) during evacuation and rescue operations.

Data sharing between BIM tools and fire and evacuation simulation tools was the focus of some papers [60–62]. Dimyadi et al. compared the two ways of sharing BIM information with a fire simulation tool: BIM rule language (BIMRL) and the Blender approach [60]. BIMRL can be used as a query engine to provide the required geometrical and some semantic data from the BIM, while only geometrical data can be shared using the Blender approach, as it requires third-party software add-ons [63]. Laasonen [61] stated that standard files are most effective when basic data like geometry and material information is transferred. In certain cases, the author suggests a combined method where complementary data from other sources of information are added to the original model. Considering the current lack of digital models, a software application for the digitalisation of printed form plans and their conversion into files readable by BIM tools was proposed [62]. The combination of spatial information and the use type of rooms is considered to provide important information for evacuation simulation.

The majority of the reviewed papers on rescue and evacuation simulations applied simple algorithms to find the shortest path [64–69], while some researchers considered other factors that affect evacuation, such as the human body's characteristics and agent behaviour features (gender, body diameter, age, possible disabilities, queuing and congestion) [70, 71], the flammability of the indoor materials [72] or smoke spread [73]. Only two works paid greater attention to modelling the effect of a combination of factors such as fire, smoke and psychological factors [74] or the occupancy density, congestion, presence of hazardous material, etc. [75].

Several of the reviewed papers aimed at integrating models for fire simulations with BIM. In the last 10 years, researchers focused especially on the integration between BIM and CFD simulations, rather than simulations based on zone models. According to Węgrzyński et al. [76], this can be explained by the belief that only CFD simulations produce good results, although the choice of the model should strictly depend on the analysis objective. In general, a smooth and direct export of useful data from a BIM tool for fire simulations was not possible. Geometrical data was retrieved from the Revit software [34] using computer-aided design (CAD) applications [77] and commercial pre-processors [78–84], but ad hoc scripts or tools were needed for the exchange of semantic data. The same occurred when the IFC open format was used [85, 86]. Within the reviewed literature sample, a solution to store simulations results in the BIM database so that they are available to other stakeholders during the life-cycle of the building was provided in only two cases [84, 87].

In some cases, game engines and virtual reality (VR) technology were used for simulating fire and/or evacuation, sometimes along with CFD-based tools [88–95]. The fire dynamics and smoke movement were usually made available by performing CFD simulations and importing results in the VR or augmented and virtual reality (AVR) environment. The size of building information models is considered a big issue in relation to the time required to process data, especially when a web-based platform has to be used. To address this problem, different solutions were provided in the literature: (i) importing only the geometric features and some fundamental semantic data from BIM into the game engine [89]; (ii) technologies for lightweight pre-processing of data [90–92]; (iii) cloud computing technology [95].

In a few papers, integrated systems for BIM and fire/evacuation simulations were developed. The researchers had to solve information exchange issues and they applied different strategies in their proposals: (i) using a multi-model approach [96]; (ii) relying on an external database [97]; (iii) developing a plug-in for visualising the results in BIM [98]; (iv) designing a fire compliance model MVD schema [99]. The need for creating new systems shows that the current building information models are not adequate for fire-related applications.

3.1.3. Code and Model Checking When dealing with safety, it is fundamental for the designer to assess code compliance and this is especially valid for fire-related regulations. To automate and optimize the process of code and model checking, some researchers proposed using BIM tools and evaluated the feasibility of such activity. In particular, the latter was the scope of a paper published in 2019 by Kincelova et al. [100]. After comparing different existing tools, the authors concluded that the existing code-checking solutions do not give adequate answers to the fire protection challenges and the BIM driven design process lacks integration. A general comment reported in almost every paper with this domain is that building information models are not semantically rich enough to perform the code and model compliance checking directly. However, considering that code compliance is necessary for a project, attempts to make fire regulations computer-readable were made in many different countries [99, 101–109] in order to automate a time consuming task. This is the case of the England and Wales building regulations for dwelling houses and the associated semantically rich object model, which contains refinements of the existing IFC entities [101]. The paper ‘‘Fire risk in relation to BIM’’ [102] explains the steps to assess fire protection solutions according to the Czech National Standard (CSN) in a BIM environment. A verification method prescribed by the New Zealand Building Code for the performance-based design of buildings related to fire safety was used as a case study to show how compliant design procedures can be modelled through the open standard business process model and notation (BPMN) language, and be translated into a computer readable format [99, 103]. A Revit [34] add-in called automated plan review (APR) was written by Clayton and Thompson [104] with the aim of checking a building design against the provisions of the International Building Code (IBC) developed in the USA. It shows the code check results within the software as text and links back to the BIM for visualisation purposes. Another Revit [34] plug-in was developed to verify the conformity of projects with the fire department standards of the State of Minas Gerais in Brazil [105, 106]. The development stage results of a stand-alone automated code compliance checking system for the Turkish Fire Code were published by Balaban et al. [107] and some parts of the Turkish Fire Code were translated into an electronically readable file format using the extensible markup language (XML). By using a flow-based, visual programming language and the standardized central platform for building information exchange called BIM+ as the database, the CodeBuilder plug-in for Allplan [110] was developed [108]. This plug-in allows the implementation of a semi-automated compliance check for a part of the German Fire Code. A BIM based code-checking method for the National Building Code of Canada was developed by Kincelova et al. [109] in 2020. The paper focuses on tall timber buildings and considers architectural and structural interfaces of the fire concepts (fire-resistance rating, flame spread rating, etc.). Other interfaces such as those that can be found in the MEP BIM are not investigated.

In all these cases, only a small part of the national code was analysed and it was not always possible to extract a unique interpretation of the text. Moreover, the interpretation of fire codes by software applications becomes even more challenging for performance-based codes.

3.1.4. Detection, Monitoring and Emergency Management This domain refers to the real-time integration of BIM and fire safety aspects, more specifically, the detection and monitoring methods/technologies, and the management of rescue and extinguishing operations, once the alarm is sent. Papers on fire detection [111–113], monitoring of facility management (FM) data and real-time situations [84, 114–124], and supporting fire-fighter rescue operations and evacuation [125–141] are grouped under this domain.

In Shiau et al. [111], a web-based system for fire-control surveillance was created and fire control equipment was integrated into the building using BIM. If a fire detector is activated, a monitor makes it possible to determine whether the warning is authentic and to immediately identify information relevant to the area on fire. The BIM of ancient buildings was pre-processed and the format was converted through cloud computing for real-time monitoring by Ji et al. [112]. Bi et al. [113] developed a system for fire control on an urban scale. The remote fire monitoring system was connected to the Internet allowing for better planning of fire brigades operations.

The majority of the reviewed papers focusing on the monitoring of FM data and real-time situations utilised real-time data from sensors. Among these, the results from CFD simulations stored in a database were used to provide evacuation guidance in two papers [84, 117]. Other proposed applications were: the extension of the IFC format [114, 115] or a BIM add-on [116] to include necessary data for emergency operations and FM, the integration of AVR technology for better planning and monitoring of FM facilities [124], the integration of a deep learning technique and semantic metadata, and using visual and thermal cameras for situational awareness [120, 121] or data from the network of sensors [122].

Only five papers attempted to provide solutions to support fire-fighter operations; of these, four address issues related to the rescue of people inside the building [135, 136, 138, 139] while Chen et al. [140] focused on the management of fire-fighting equipment outside the building. For instance, domain-specific route graphs were created by using object-based (IFC class types) space partitioning to provide a spatial assistance navigation system [135]. The system, mounted on the fire-fighters' helmets, would show the features of a room on the transparent display on the helmet's mask to help orient the rescuers.

In general, papers on the support of fire-fighters rescue operations and evacuation focus on localisation technologies. The solutions proposed for the evacuation of occupants in the reviewed papers often rely on the hypothesis that building occupants will use their smartphone during a fire [126–132, 134].

3.1.5. Investigation of Causes of Fire This application domain contains the lowest number of papers, even though inspections after a fire are common activities for fire-fighters. 3D BIM tools have been used in Lin et al. [142, 143] to support investigations of fire causes. Handheld devices which are light, inexpensive and user-friendly convert the fire disaster investigation evaluation, traditionally carried out in paper format, into electronic form. Fire investigators can record information immediately and increase the accuracy of the fire site evaluation. Photos taken on the fire scene can be visualised on the 3D model, helping investigators to better understand the dynamics of the fire event.

3.1.6. Fire Safety Equipment Modelling and Maintenance The fire safety equipment modelling and maintenance application domain contains papers discussing the use of BIM tools for the FM phase of the building life-cycle and focusing in particular on fire safety equipment management.

An aspect investigated by three papers was the cost-estimation of fire safety equipment [70, 144, 145]. BIM tools can in fact easily and automatically support the calculation of quantities and costs associated with objects contained in the 3D model. Visual programming was employed to provide a rule-based fire-fighting equipment installation plan and bill of quantities (BoQs) for portable fire-fighting equipment [70]. Another proposal was about the development of a web-based hybrid BIM cost-estimation system using the web-based technology. The system incorporates BIM with external cost estimation data, allowing the user to view and modify the project via a web-browser and export the cost analysis results as a report [144]. The fire risk index method (FRIM) was integrated with a BIM tool and a FRIM add-on was developed in the study by Schatz and Rüppel [145]. FRIM is a semi-quantitative method applied for the evaluation of the fire risk of multi-storey buildings. In the paper, information about the influence of individual fire safety deficiencies (i.e. technical, structural fire protection elements/components) on the security level of the whole building was combined with the associated costs.

Another area of interest for papers grouped under this domain is the inspection and maintenance of fire equipment [146–148]. The modelling of FM processes using the BPMN language made it possible to define the information exchange requirements for healthcare facilities with the aim of extending BIM functionalities to FM personnel's operation and maintenance activities [146]. Urban components management is the research focus of Zhang et al. [147]. They combined the geographical information system (GIS) and BIM technologies, and created a real-time 3D Earth visualisation platform. The management of fire hydrant component in a building was shown as an example. The BIM file format was converted to be loadable by the platform and parsed to obtain information on each model component. The user, by clicking on the fire component, can query and pop up the associated information. In the study by Khan et al. [148] an open-source blockchain service was used to prove the date of inspections and to overcome fraudulent submissions.

The use of mobile devices was proposed for maintenance purposes in several studies, such as [81, 82, 148–150]. A web-based prototype developed by Wang et al. [81, 82] supported the maintenance operations management remotely through an equipment maintenance module. The BIM allows the user to filter data, search for equipment to be maintained, and export the file to be visualised on a browser. Another research work that underlines the practicality of mobile devices for the FSE inspection and maintenance combines AR and BIM technology [149]. For the information conversion between BIM and the AR system, AR inspection points were created in the BIM and the iBeacon technology for data transmission was employed. Zhang et al. [150] describe the use of collective intelligence for mass inspection tasks through a mobile app called iInspect. iInspect users perform an inspection on listed fire equipment items in a building by uploading photographs and filing a report. Fire safety managers would be notified with information about the severity of the issue if a problem is detected. This research integrated BIM, VR and indoor real-time localization systems to facilitate FSE inspections.

Neural network and AR were also combined with BIM to enable inventory, information retrieval and information update directly on-site [151, 152]. In the study by Corneli et al. [151], an AR interface was developed for a head-mounted display. The automatic recognition of objects in the field of view of the user and their placement into the BIM was made possible through deep learning [151]. Deep learning methods for neural network training reached an accuracy rate of 76% for testing 102 objects across 10 classes in similar research [152].

All the applications mentioned in this section made use of add-ons or developed platforms or software applications other than BIM tools, revealing how the building information models are not yet adequate to cover the whole of the life-cycle phases of the building, especially the FM phase.

3.1.7. Education and Training One of the most effective feature of BIM tools is the three dimensional representation of space for education and training purposes. Almost all the papers grouped under this application domain involve the integration between BIM and Game-AVR technology [71, 80, 89, 90, 92, 98, 131, 153–155].

In Kanak et al. [156], GIS was the main technology to be integrated in the BIM environment but the authors also used AVR and Internet of Things (IoTs) technologies to increase the preparedness of citizens during crisis situations. Only two publications used the BIM without any other technologies [81, 82]. In these studies, the results from CFD simulations served to identify areas that contain hazardous materials or areas likely to cause disasters. A 3D map (where the hazardous areas and escape routes guidance are shown) was created and this was used to make a video for citizens' awareness.

In [80, 153], a smoke visualisation method was proposed for creating the fire rescue scenario and achieving a highly realistic visualisation. Texture and illumination features were added to the BIM for reducing the modelling workload. Also, VR devices could be used to control actions and viewpoints. In another research study [89], fire simulation results from FDS and the BIM were combined in the VR environment to enable trainees to experience physical collisions with occupants in virtual evacuation drills. A mobile Web3D system was proposed for real-time fire evacuation training, where lightweight BIMs and FDS simulations results were utilised [90, 92]. In Wang et al. [131], BIM and VR were also used to involve the end user in the refinement of building emergency plans. In the same research work, evacuation training and guidance through various mobile devices was provided by the proposed system.

In Kanellos et al. [98], a system module called PYRONES was dedicated to the training of individual first responders and resource managers in indoor scenarios. The system highlights areas of interest, displays charts, statistical information and several other aspects. Rüppel and Schats [93, 154] proposed a virtual training engine where the use of heating jackets or radiators and other devices is thought to offer a more realistic training environment for fire-fighters. Hong and Lee [71] demonstrated the effect of human behaviour simulations on the evacuation plan design. During an architecture course, students were asked to design the evacuation plan according to legal prescriptions. In a second phase, they were asked to refine the same evacuation plan using a human behaviour simulation platform. Analyses performed with the platform changed significantly the evacuation plans proposed by the students. Finally, the approach proposed by Khan et al. [155] includes the training of workers in a building by integrating VR technology.

BIM and FSE integration solutions for education and training purposes are mostly provided by researchers investigating other topics such as fire and evacuation simulations, and then using the results also to enhance awareness for rescuers and citizens. Only five papers [131, 153, 154, 156] were specifically dedicated to education and training.

3.2. Technologies Supporting BIM–FSE Integration

In the majority of cases, the BIM environment was considered sufficient to provide solutions for FSE applications (e.g. [101, 102, 146, 157]), although the inclusion of programming scripts (e.g. [53, 55, 64, 85, 158]) and the use or development of plug-ins (e.g. [50, 56, 58, 62, 70, 104, 105, 108, 116, 125, 139, 145]) was needed to enhance the functionality of the BIM tools. The BIM–FSE application domains that mainly rely just on BIM are fire safety design, code and model checking, and the investigation the causes of fire.

Figure 3 shows that CFD and agent based modelling (ABM) based technologies were the most commonly used in fire and evacuation simulations, sometimes in combination with Game-AVR technology. The combination with other technologies is also required for the detection, monitoring and emergency management domain. In this case, IoT, deep learning and video cameras were the most utilised technologies and this is in line with the need for real-time data for such applications. However, CFD and Game-AVR technologies were also quite often used, revealing the importance of a good knowledge of fire phenomena, through previous analyses, to interpret data from sensors, and of clear and realistic visualisation of the 3D space. For the remaining domains (i.e. fire safety equipment modelling and maintenance, and education and training), the Game-AVR technology was the most applied.

The trend in the technologies supporting the BIM–FSE integration is shown in Figure 4, where after excluding the 42 papers that only rely on BIM-based technology, the number of papers dealing with technologies other than BIM is illustrated. Papers mentioning different technologies were counted in more than one category. In general, the CFD-based technology is the most commonly employed to support the BIM–FSE integration across the identified application domains, followed by the Game-AVR and IoT-based technology. Deep learning or artificial intelligence and blockchain technologies that are currently gaining momentum in other industrial sectors are seldom mentioned in the reviewed papers (i.e. [120, 148]).

4. Discussion

The presented literature review refers to papers published in the last decade and the distribution of selected papers according to the year of publication is reported in Figure 5. The integration of BIM and FSE is clearly becoming a topic of interest. The research trend has been increasing especially in the last 5 years, highlighted by the twofold increase in publications from 2015 to 2020. This section

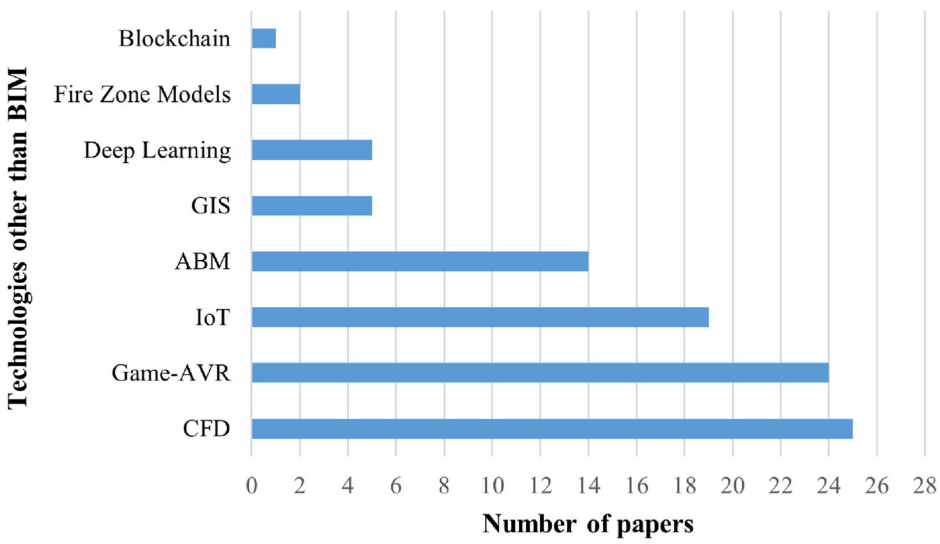

Figure 4. Distribution of reviewed papers according to technologies other than BIM supporting the BIM–FSE integration.

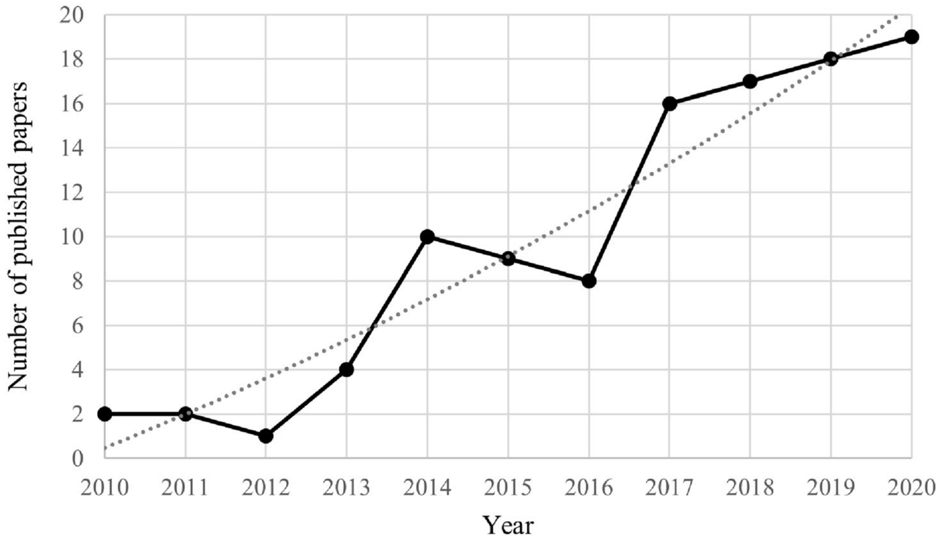

Figure 5. Distribution of reviewed papers according to publishing year.

attempts to evaluate the benefits and current limitations of BIM–FSE application domains and supporting technologies.

4.1. The Potential of BIM–FSE Integration

The selected 106 papers addressed different aspects of fire safety, demonstrating the wide range of actions available for the improvement of fire safety management. The potential of BIM as a systematic risk management tool was mainly utilised in other areas rather than fire safety. Zou et al. [159] underline that the management of construction personnel safety during the construction phase has been the main interest so far. Fire risk assessment in particular is a topic barely investigated by researchers. Assessing fire risks for a building requires information about its category (public, commercial, educational building, etc.), geometry, materials used, structural performance, HVAC system, fire detection and suppression systems, space occupancy and other characteristics [160]. Building information models represent an ideal, time-efficient centralised repository for storing relevant data about various aspects of a building. If the information is stored in the centralised model and correctly updated during its life-cycle, the analyst can access the stored data during the renovation phase to verify whether changes in the building design compromise occupants safety.

The major benefits of the BIM–FSE integration recognised in the reviewed papers are related to the time savings and reduction of errors as data is retrieved from the BIM (e.g. [78, 151, 161]). The 3D BIMs have been reused for several purposes such as graph construction, route finding and network analysis. Furthermore, BIM processes can prevent mistakes by reducing the incorrect information gained from 2D drawings [68].

Automation of data management tasks and the enhanced visualisation in three dimensions (e.g. [98, 104, 140]) are other incentives for fire engineers to use BIM tools. In addition to this, the use of a BIM as a centralised collector of geometric and semantic information, added during different phases of the building life-cycle, supports and optimises management processes related to fire prevention and protection [87].

Performance-based design is considered too time-consuming and require significant skills, making the integration process complex to address. Nevertheless, the majority of the reviewed papers were centred on fire and evacuation simulations, revealing that the research community perceives the strengths of the integration between BIM and performance-based approach for fire safety. Applying a performance-based approach can address the unique features and uses of a building, increasing the cost-effectiveness of the designed fire safety measures. Performance-based design can help investigate low-frequency scenarios, which in the majority of the cases also imply the worst fire consequences. A rich source of information such as a building information model can definitely be seen as a facilitator for the application of such methods. The knowledge and experience of the person in charge of assessing fire risk and safety strategies is fundamental and BIM should be considered just as a tool to facilitate this work. The combination of experts' knowledge from the BIM and FSE fields, and the availability of advanced technological tools is an opportunity to conceive new ways for the integration of complex methods such as performance-based design in common practice.

The IFC standard for openBIM data exchange makes the integration of different technologies easier and vendor-neutral, improving collaboration among different professionals. Design choices can be compared in a 3D virtual environment, increasing the flexibility of design processes and speeding up the validation process. Furthermore, the possibility to store the information about the building in a single virtual model supports the management of the real building by facilitating decision making processes. The possibility to integrate several technologies and techniques such as the IoT, deep learning, AVR, and artificial intelligence, has great potential for the development of more automated and effective methodological and technological solutions in the field of FSE.

4.2. Technology Limitations

The use of a comprehensive BIM as a basis for data exchange aims at optimising the building life-cycle management by enhancing communication among the different stakeholders, processes and tools. A wide range of BIM tools already exists for different application areas [13]; however, many of them have limited support for data exchange and, because of this, they are called *islands of automation* [162]. To overcome this issue, a standardised data exchange format to export or import geometric and semantic data from one application to another is required. An essential characteristic of this format should be the loss-free exchange of data between software applications from different vendors [10]. A neutral vendor format is also what many countries are requiring in public tenders to ensure impartiality.

The analysis of the file exchange formats and BIM tools used in the reviewed papers revealed that the majority of BIM–FSE applications adopts proprietary (or native) formats of Revit [34] and other Autodesk tools, as shown in Figures 6 and 7. The prevalent use of native file formats could lead to the adoption of a *de facto standard*, defined as "a set of criteria for software, hardware, or communications procedures that is widely accepted because of the dominance of a particular technology over others rather than the action of a recognized standards organization" [163].

On the contrary, working with open standards enables coordination among different systems and data sharing. The IFC format, for instance, has been developed over the last 20 years to address the interoperability and integration of structured data and, as illustrated in Figure 6, it is the most used for BIM–FSE applications. However, even when an open standard is used, interoperability issues were reported by the authors of the reviewed papers, such as [52, 61, 62, 126, 157]. This can be explained by the differences in IFC files of the same model, generated by different software.

A limitation of the IFC format is its limited applicability across the building life-cycle [52]. IFC schema extensions [114, 115], refinement [101] or MVD [99] were then proposed for fire safety, even before the time period covered by the systematic review [32, 164–166]. In general, a lack of semantically rich building information models was underlined in the reviewed sample of papers, so in many cases the missing data had to be added manually or imported through developed scripts [56, 60, 62, 93, 101]. The Level of Detail—LOD—(ISO 19650) of BIMs for FSE applications was mentioned in a few cases: Wang et al. [81, 82] used a LOD 200 BIM, Sun and Turkan [83] a LOD 300 BIM, and Kanak et al. [156] a LOD 400

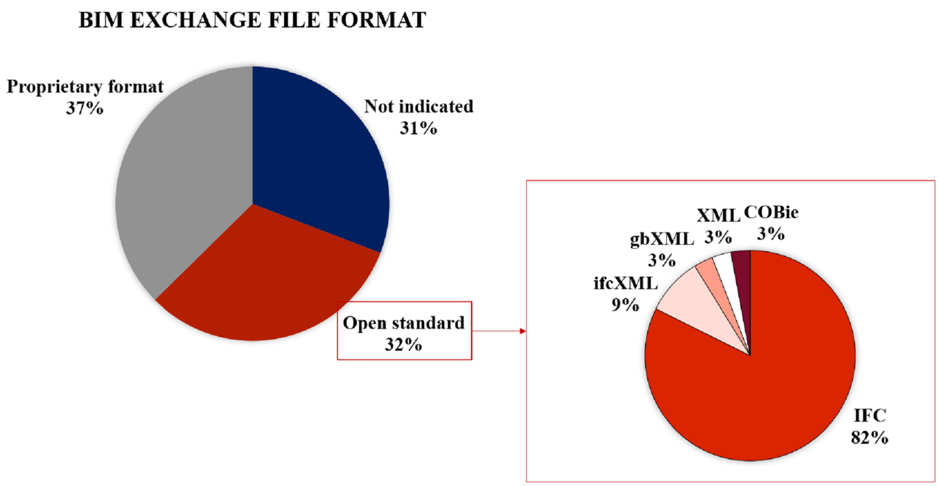

Figure 6. Distribution of BIM exchange file formats used in the 106 reviewed papers.

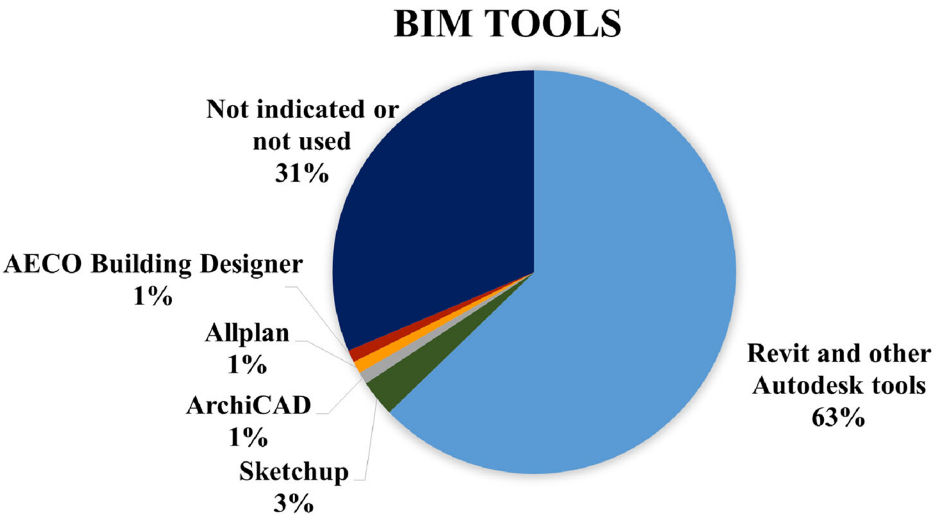

Figure 7. Distribution of BIM tools used in the 106 reviewed papers.

BIM. However, in Kincelova et al. [109], it is claimed that automating the verification of assemblies requires a level of detail of LOD 400 but such details are not transferred through IFC format for the FSE domain. The full building information model cannot be supported and implemented by many specialised domain applications [167].

Finally, the coupling between BIM tools and other technologies is still in its exploratory stage. In 64 reviewed papers that integrated technologies other than BIM, the use of a specific BIM tool was explicitly mentioned. In 72% of these, the development of plug-ins, ad hoc scripts or the use of pre-processors was necessary to make the coupling possible, since a smooth connection was not available.

4.3. Gaps in the Life-Cycle Oriented Approach

In the literature, a "BIM dimension" is considered as a measure of the information capacity of BIM integrated environments [168]. Information hierarchies are intended to address specific tasks according to the project life-cycle phase and complexity. A progressive system, starting from number 3 and coupled with the letter "D", was used to indicate the BIM information richness according to the BIM use case, namely the model purpose.

However, if the 3D commonly indicates the virtual model that expresses mainly visually the design concepts through the three spatial dimensions, the 4D relates to planning and time scheduling, and the 5D identifies budget monitoring and cost analysis. There is a lack of consensus beyond the fifth dimension [169]. Some sources assigned different information capacities to the 6D [170], 7D [171] and 8D [172]. In this paper, the 6D is considered the last dimension, and is associated with the FM phase and project life-cycle information according to the NBS convention [173].

The BIM approach is considered to be particularly focused on the design and construction phase in the literature [15–18]. This implies that the 3D and 4D are the most investigated dimensions. The literature review reveals that this assumption does not reflect the situation about BIM–FSE applications. Actually, a consistent number of reviewed papers also deal with FSE issues of the 6D. This is mainly due to the fact that emergency management is one of topics most explored by researchers. Fire safety is often checked at the end of the design phase according to the prescriptive regulation requirements. The 3D is considered useful to retrieve the building geometry for fire and evacuation simulations, while only three papers relates to the 5D and none to the 4D. Shifting to a performance-based design requires a system-thinking approach [174], where the safety strategy is integrated starting from the shape and organisation of the spaces of a building. The retrieval of information from a shared Common Data Environment (ISO 19650) is a key aspect of BIM. However, the data from a specific building life-cycle phase or use case was stored and made available to other stakeholders or for future analyses only in a few papers [56, 84, 87, 97, 117]. The lack of concern about the definition of standardised flows of information among stakeholders involved in fire safety is a crucial methodological gap in BIM–FSE integration. The prescriptive approach is still quite dominant in fire safety design, code compliance checking and evacuation simulations using BIM. There is a lack of BIM–FSE engineers or certified training courses aimed at creating professionals who can facilitate the adoption of performance-based methods within a life-cycle oriented approach.

5. Future Research Directions

The BIM approach, by going beyond the 3D geometric modelling, attempts to encompass the management of all the project life-cycle phases. The most exploited functionalities of BIMs in FSE applications are the visualisation capabilities and the retrieval of building related data. However, some BIM–FSE potentialities are still not fully harnessed. The findings of the systematic literature review conducted in this paper can help identify possible future research directions to overcome the limitations and benefit from the advantages discussed in 4.1. The research agenda for the digital transformation of FSE through BIM is summarised in Figure 8.

Current research reveals that building information models are seldom semantically rich enough to handle the fire safety terminology and the effort required by fire engineers varies according to the LOD of the BIMs provided to them. This shows a lack of standardised processes and information requirements, that would also clarify roles and responsibilities, defining the professional profiles required in each phase.

The quantity of data that the IFC data model provides may exceed the data needed for particular use cases and process phases. Also, a fully integrated IFC schema does not consider the ways in which information is shared by practitioners. In order to solve these issues, uniform and standardised ways to regulate which information is delivered by whom, when, and where in the data model is

PONTENTIALITY/BENEFITS	LIMITATIONS (T=Technology; M= Methodology)		FUTURE RESEARCH DIRECTIONS
Enhanced Fire Risk Assessment	T	Topic barely investigated by researchers	• Creation of a database for the quantification of fire consequences and likelihood of events, included in a BIM based framework • Model View Definition (MVD) for risk assessment
	T	Lack of BIM models containing semantic data required to perform fire risk assessment	
	M	Fire Safety not integrated in the early stage of the design process	
	M	Investigations after a fire do not usually harness BIM technology	
	M	Lack of system thinking approach	
Automation of data management tasks and information sharing	T	Limited support for data exchange	• Definition of standardized processes and information requirements • Management methods for building changes and their impact on fire safety
	T	Interoperability issues with open standards	
	T	Prevalent use of proprietary formats	
	T	Lack of semantically rich BIM models	
	M	Lack of standardized practices of information exchange among stakeholders	
Facilitating the application of the performance based approach	T	BIM models not supported by specialized domain applications	• Model View Definition (MVD) for fire and evacuation simulations • Definition of standardized processes including roles and responsabilities (professional profiles required)
	M	Fire safety design, Code compliance and evacuation simulations are still mostly based on prescriptive approach	
	M	Lack of BIM-FSE experts and specific training courses	
	M	Lack of system thinking approach	
Supporting decision making processes through the integration of other technologies	T	The coupling between BIMs and other technologies is still in its exploratory stage.	• Model View Definition (MVD) for fire monitoring • Big Data management and Data Analytics; Blockchain

Figure 8. The research agenda for the digital transformation of fire safety engineering through building information modelling.

necessary. The IDM/MVD frameworks were developed to address this purpose. MVDs have been developed according to the open standard information delivery manual (IDM, ISO 29481-1:2010). An information exchange framework harmonizes the development of the IDM information exchange requirements and MVDs into a completely consistent approach [175]. Fire safety applications cover a variety of specific use cases, each requiring different sets of information. For this reason, the authors suggest that more than one MVD should be provided for FSE, in addition the the ones already identified by BuildingSMART [19, 20]. In particular, three main use cases are identified: fire risk assessment, fire and evacuation simulations (which correspond to the BuildingSMART MVDs) and fire monitoring. The proposal aims at facilitating the retrieval of information from BIM according to the specific activity to be undertaken by the fire engineer.

The possibility to store data and to make it available to different stakeholders and for different life-cycle phases is a relevant aspect of the BIM approach. However, there were no studies in the literature dealing with the management of changes in the building. These changes often occur during the life span of a building, for example during renovation, energy retrofitting or change in the use of spaces. The assumptions made for the previous fire safety analyses might become invalid when the building design changes. An evaluation of the influence these changes have on the fire safety becomes necessary and the BIM approach might have an important role in the automation of operations, saving time and reducing costs.

The IoT technology is applied in about 20% of the analysed sample of papers, after CFD and game-based technologies. The availability of real-time data in fire emergency management is a powerful tool and the IoT technology provides the opportunity to incorporate data from sensors in a BIM-based monitoring environment. However, the BIM–IoT integration poses new challenges in relation to interoperability and the handling of a dynamic environment. Moreover, the coupling of semantically rich BIMs and data from sensors leads to new research topics, focusing on big data management and data analytics. The life-cycle of a building involves different stakeholders and, among them are public authorities who are responsible for verifying and validating projects and changes to the buildings. Technologies such as blockchain are emerging as a valid tool to guarantee data security and tracking and should be integrated in the fire safety domain as well.

6. Conclusion

This paper provides an overview of BIM and FSE integration through an in-depth review of 106 papers published in the last decade with the aim of identifying the benefits and potentialities, limitations and future research directions for such integration, facilitating the digital transformation process of FSE.

The systematic literature review method, defined by five steps, was applied to answer the research questions. The application of the systematic review method led to a limited number of reviewed papers and observations made by the authors are based on the analysed literature. As common practice, the keywords search was restricted to the title, abstract and authors' keywords fields. This allows an immediate view on the topic. Papers were searched for in the Web of Science and Scopus databases considering their relevant role according to several scholars.

However, the review cannot be considered exhaustive. A greater number of publications can be studied by integrating search results from the Google Scholar database or extending the keywords search to the papers' full text rather than only in the title, abstract and author keywords. Papers published after 2020 can be discussed to bring the review up to date in a future work. Furthermore, considering that the BIM technology is becoming part of the professional activities, the actual maturity level of the BIM–FSE integration might be higher and cannot be estimated through the study of scientific publications alone.

The reviewed papers were classified according to seven application domains and the main technologies other than BIM that supported the BIM–FSE integration. A quantitative measure of the BIM–FSE integration trends in relation to the year of publication, application domains, supporting technologies, information exchange formats, and BIM tools employed was provided in the review. The papers published in 2020 are almost ten times as many as those published in 2010, revealing the increased interest in the matter. The most investigated domains are fire and evacuation simulations followed by detection, monitoring and emergency management. These results are reflected in the technologies that, together with the BIM-based technology, were used the most to support FSE applications: CFD, Game-AVR, IoT and ABM. Proprietary formats and commercial tools are more often used in spite of BIM being promoted as the facilitator of information sharing among stakeholders.

The potential of the BIM–FSE integration was highlighted and the main current limitations to achieve such potential are discussed. The observed benefits and limitations made it possible to propose future research directions that were described to support scholars and practitioners in their activities and to foster research interests for the future.

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