Fire Safety with the Application of BIM for Historic Buildings: Systematic Review

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Abstract Historic Building Information Modelling (HBIM) is characterised by the potential to manage and disseminate information about the built heritage. This review aims to investigate the recent tools and technologies carried out so far against fire in historic buildings. From the research in five databases, Scopus, Web of Science, INSPEC, Academic Search Ultimate and Current Contents Connect, from 2016 to 2021, 91 articles were initially selected, and after critical analysis, 25 relevant studies were collected for this review. The results indicate that few approaches were developed to evaluate the use of BIM in the analysis of fire safety in historic buildings, the relevant articles collected involving this theme were limited to presenting a methodology for adequate performance evaluation, as well as to configuring a procedure for interoperability between programs, moreover, to a mechanism to assist evacuation without significant changes in structure. However, when only the relationship between fire safety and historical building is evaluated, the results indicate a more significant number of studies that can be grouped into different approaches: Proposals of New Measures, Update on Implemented Measures, Evaluation of Fire Protection and Fire-Resistant Material. The results show that there are several methods to assess and improve the buildings protection against fire and the implementation of HBIM is an important tool which will improve the understanding of the past, the present and provide the tools for the safe future of historic buildings.

Keywords Historic buildings · Old buildings · Fire safety · Building information modelling (BIM) · Historic building information modelling (HBIM) · Evacuation

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1 Introduction

The fire protection project of a historic building represents a challenge due to the need to achieve an adequate level of safety in a building with many design restrictions (Torero 2019). Significant risk levels affect the built heritage due to its fundamental characteristics, presence of different hazards and high exposure (Bernardini et al. 2016). It is essential to define a methodology based on an integrated digital design procedure to protect the historical heritage, aiming to manage fire safety (Frosini et al. 2016). The use of Building Information Modelling (BIM), in particular the Historical Construction Information Modeling (H-BIM) approach, for fire safety purposes has been studied many times based on improper principles (Torero 2019). The "proper" evacuation of the building depends mainly on the perception of the spaces of the individuals, the architectural layout, and the presence of adequate signalling systems (Bernardini et al. 2016). One possibility for fire prevention analysis would be interoperability between HBIM models and open-source software (Frosini et al. 2016).

Research shows several studies related to fire safety in historic buildings, fundamental to enable the correct use of BIM or HBIM tools for the safe future of built heritage. To maintain the safety of the historic building, it is necessary to add active firefighting equipment (Chang et al. 2021). The combination of UFSM (Urban Fire Spread Model) results with Fire Dynamics Simulator (FDS) can help analyse the risk factors of input data and contribute to the improvement of cultural heritage building protection technology (Huang 2020). Implementing complementary security measures can help mitigate negative impacts and limit costs, such as an automatic entry flow control system for people in the building (Caliendo et al. 2020). To reduce catastrophic risks in buildings, a risk reduction programme is intended to implement standards, regulations and resolution of imperfections of standards (Shakib et al. 2018).

The preservation of historic buildings depends on a use compatible with their structural capacities and regular maintenance (Vijay and Gadde 2021). One of the critical factors in achieving robust fire safety in historic buildings is updating physical fire protection measures (Kincaid 2018). The optimisation of the functional purpose of renovated spaces in historical buildings allows the implementation of fire protection without further modifications to the original structures (Iringová and Idunk 2017). Most original historic buildings are not suitable for occupancy if we consider hygiene, static, thermal and fire protection (Iringová and Vandličková 2019). In addition, to increase the building's performance, it is essential to conduct analyses to determine fire resistance, such as historical systems of wooden arch floors submitted to different exposures to fire (Garcia-Castillo et al. 2021). The development of sustainable building materials, such as artificial pozzolans, increases the resistance of restoration mortars at high temperatures, decreases damage to historic buildings during the fire and contributes to cultural sustainability (Demircan et al. 2021).

However, no comprehensive review was identified to promote the integration and optimisation of heritage information constructed through HBIM to ensure fire safety in historic buildings. Thus, a literature review is proposed to identify knowledge gaps and validate the need for continuity and deepening of future research that can contribute to better understanding the past and the present and provide the tools for the safe future of historic buildings.

2 Methodology

Five electronic databases were used to develop this review: Scopus, Web of Science, INSPEC, Academic Search Ultimate and Current Contents Connect. The search was divided into two phases. In the first phase, the keywords were combined as follows: ("Historic Buildings" OR "Old Buildings") and "Fire Safety" AND (BIM OR HBIM). Due to the low number of articles obtained, a second search phase was considered. The authors decided to eliminate the keywords BIM and HBIM initially used, as follows: ("Historic Buildings" or "Old Buildings") and "Fire Safety". As a result, the number of articles found in the second search was 240, much higher than the seven articles found in the first phase. The search targeted fields were Title, summary and keywords for Scopus. Title and summary were applied to INSPEC and Academic Research. At the same time, the search of the keywords was for topics on the Web of Science and Current Content Connect. For the selection of studies, a screening process was carried out based on the following parameters: year of publication defined from 2016 to the present—we chose the last five years to have the latest data/methodologies, type of document of research articles of source type of peer-reviewed journals, and language of articles written in English—see Table 1. Then, the results were analysed, the studies related to the research theme were selected, and the duplicate records were eliminated.

The eligible studies were classified into four categories according to the article's content: (1) proposals of new measures, (2) updates on implemented measures, (3) evaluation of fire protection and (4) resistance of the material to fire. This process was carried out using a customised table to collect information of interest that mainly involved: references and country, objectives, methodology, results and limitations, target groups, equipment, evaluation method and its limitations.

3 Characteristics of the Selected Studies

3.1 Selected Studies

Through the searches in the databases, 247 articles were initially collected. Using the filters provided by each database (Table 1), restrictions were applied that resulted

Table 1 Data base search summary

Database	Filtros da Pesquisa 1
Scopus	(TITLE-ABS-KEY ("Historic* Buildings" OR "Old Buildings") AND "Fire Safety" AND (BIMORHBIM)) AND (LIMIT-TO (PUBYEAR, 2021) ORLIMIT-TO (PUBYEAR, 2019) ORLIMIT-TO (PUBYEAR, 2018) ORLIMIT-TO (PUBYEAR, 2017) ORLIMIT-TO (PUBYEAR, 2016)) AND (LIMIT-TO (DOCTYPE, "ar") ORLIMIT-TO (DOCTYPE, "cp") ORLIMIT-TO (DOCTYPE, "ch")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j") ORLIMIT-TO (SRCTYPE, "p") ORLIMIT-TO (SRCTYPE, "k"))
Web of science	((TS = ("Historic* Buildings" OR "Old Buildings")) AND TS = ("Fire Safety")) AND TS = (BIM OR HBIM)
INSPEC	((("Historic* Buildings" OR "Old Buildings") AND "Fire Safety" AND (BIM OR HBIM)) WN KY)
Academic search ultimate	AB ("Historic* Buildings" OR "Old Buildings") AND AB "Fire Safety" AND AB (BIM OR HBIM)
Current contents connect	TOPIC: (("Historic* Buildings" OR "Old Buildings")) AND TOPIC: ("Fire Safety") AND TOPIC: (BIM OR HBIM)
DATABASE	FILTROS DA PESQUISA 2
Scopus	(TITLE-ABS-KEY ("Historic* Buildings" OR "Old Buildings") AND "Fire Safety") AND (LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))
Web of science	((TS = ("Historic* Buildings" OR "Old Buildings")) AND TS = ("Fire Safety")) and 2016 or 2017 or 2018 or 2019 or 2020 or 2021 (Publication year) and article (Document Type) and English (Languages)
INSPEC	((("Historic* Buildings" OR "Old Buildings") AND "Fire Safety") WN KY) + (({ja} OR {ca}) WN DT) AND ({English} WN LA) AND ((2020 OR 2019 OR 2018 OR 2017 OR 2016) WN YR)
Academic search ultimate	AB ("Historic* Buildings" OR "Old Buildings") AND AB "Fire Safety" Publication Date: 20160101-20211231
Current contents connect	(("Historic* Buildings" OR "Old Buildings")) AND TOPIC: ("Fire Safety") Limited For: Publication Year: (2020 OR 2019 OR 2018 OR 2017 OR 2016) AND Document Type: (ARTICLE)

in the rejection of 194 articles, as follows: year of publication defined from 2016 to the present—118 exclusions, type of research paper document—34, type of source of peer-reviewed journals—0 exclusions, the language of written articles in English, 4, and relationship with the theme—38 exclusions. Among the 53 articles selected, 28 were duplicated, leaving 25 relevant articles for analysis in the current review.

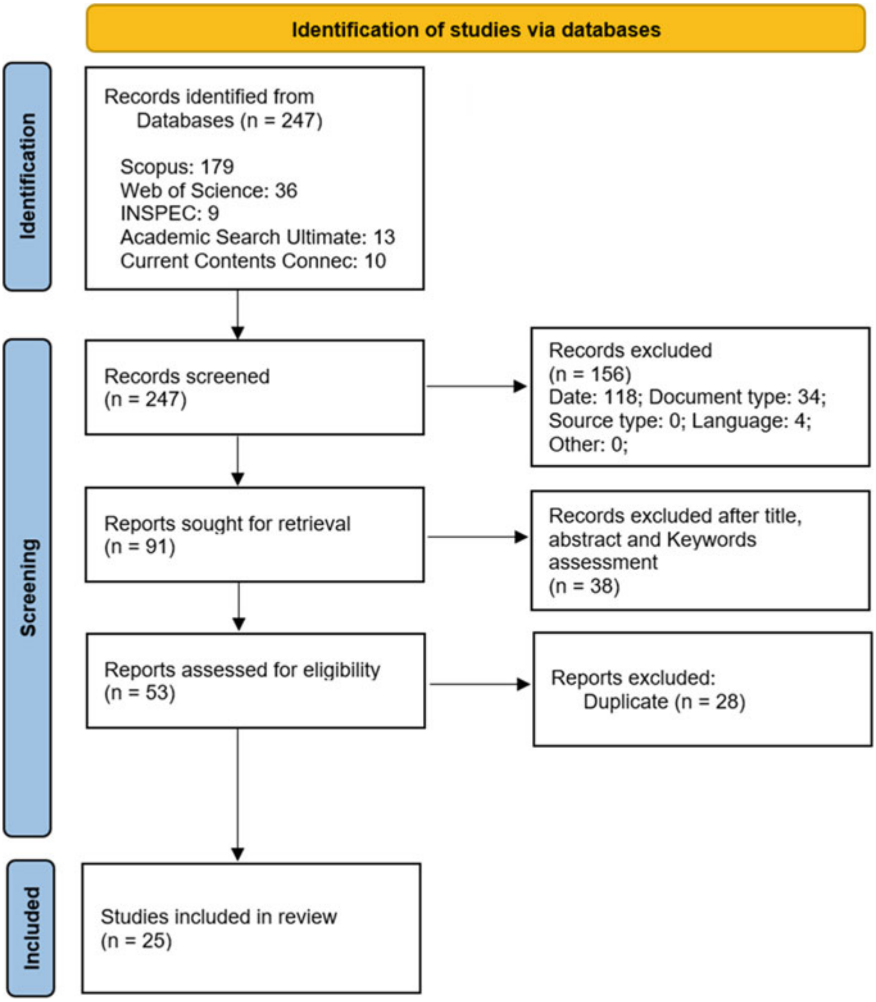

Fig. 1 Search summary, based on PRISMA's flow diagram

In Fig. 1, it is possible to overview the numbers of each stage of the methodology applied in the study.

3.2 *Characteristics of the Included Studies*

Among the 25 selected articles, in 2016 and 2021 the number of studies involving fire safety and historical building was six and five articles, respectively. However, the introduction of BIM or HBIM was addressed the most in 2016, two articles. Figure 2

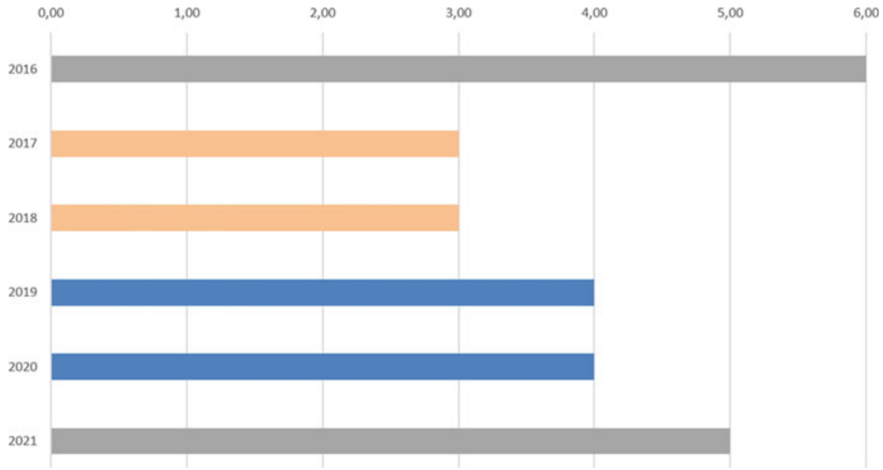

Fig. 2 Selected articles group per year (2016 until 2021)

shows the evolution of studies using this theme over the years, where it is clear that despite a downward trend of this approach between 2017 and 2018, 3 articles each year, research grows again from 2019 with four articles and five articles in 2021.

Despite the diversity of the topics of the 25 selected articles, four research areas could be identified. Among these, ten studies included presented proposals of new measures for fire safety in historic buildings. Three articles targeted updated information on measures already implemented. Four studies evaluated fire protection in specific cases. Finally, eight articles addressed issues related to fire resistance. A more representative quantity is observed among the areas involving proposals of new measures and resistance of the material to fire, as illustrated in Fig. 3.

Table 2 represents the articles grouped per their fields of study identifying the target groups, the type of case study, equipment used, and the indicators analysed of the selected studies. Among the 25 analysed articles, only five authors did not use any assessment method to test or validate their proposals, as illustrated in Fig. 4. These studies are all related to the fire resistance material field of study.

Among the ten articles in the research area that present proposals of new measures, the most common indicators are related to the evacuation of buildings in three (Bernardini et al. 2016; Caliendo et al. 2020; D'Orazio et al. 2016) studies and the spread of fire in two (Chang et al. 2021; Tung et al. 2020). In these ten cases, the software chosen consisted of most cases in SDS—Fire Dynamics Simulator (Torero 2019; Chang et al. 2021; Tung et al. 2020).

In the case of the eight articles related to the material's resistance to fire, despite the different indicators analysed, the most common studies are related to wood (Garcia-Castillo et al. 2021; Log 2016; Chorlton and Gales 2019) or masonry (Daware and Naser 2021; Demircan et al. 2021; Shao and Shao 2018). In these eight cases, the target group mainly consisted of the time (except Log 2016) in specialists, and most of them (Daware and Naser 2021; Demircan et al. 2021; Król 2016; Siligardi et al.

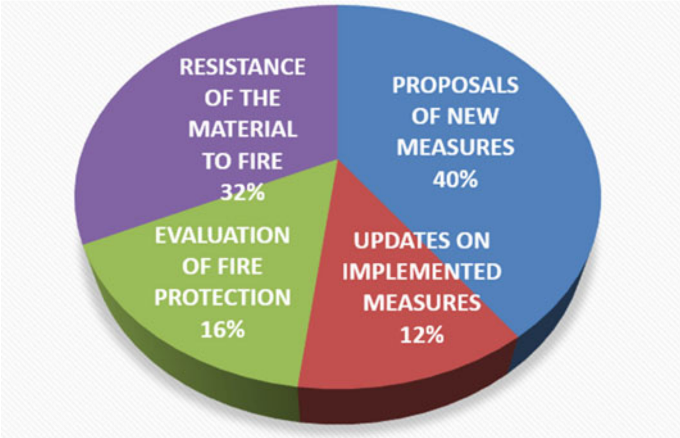

Fig. 3 Classification of articles based on the field of study

2017; Chorlton and Gales 2019) did not use the Case Study analysis method to test their proposals.

Among the seven articles related to updating information on measures already implemented (Kincaid 2018, 2019; Vijay and Gadde 2021) and evaluation of fire protection of specific cases (Iringová and Idunk 2017; Takács and Szikra 2017; Iringová and Vandličková 2019; Quapp and Holschemacher 2020).

3.3 Results Quality

After the screening process described earlier resulted in the exclusion of 156 articles, as shown in Table 1, 38 other studies were excluded because they did not present any relation with the objectives of the current review. All selected articles had their abstracts and conclusions read. After discarding the 28 duplicated articles, relevant articles full text was read, following a critical analysis and identifying their main contributions and limitations. Despite the weaknesses observed in some articles, mostly related to the structure of texts, the selected studies, in general, were considered fit in terms of quality, mainly because they presented relevant results. Most of the selected studies have at least one citation, between 1 and 33 citations, which indicates the quality of the articles.

Table 2 Characteristics of the studies grouped by their field of study

Study field	Target groups	Case study	Equipment	Indicators	References
1. Proposals of new measures	Owner, design	Educational building		Critical vision	Torero (2019)
	Owner, design, user	Theater/Museum/Cultural building	FDS + EVAC	Evacuation time	Bernardini et al. (2016)
	Design	Educational building	Model checking	Traditional and automated analysis	Frosini et al. (2016)
	Owner, design, user	Religious building	FDS	Banks on fire	Chang et al. (2021)
	Design	Castel/Palace	UFSM FDS	Risk factors	Huang (2020)
	Owner, design	Residential/Multiuse building	FDS	Fire growth and spread	Tung et al. (2020)
	Owner, design, user	Theater/Museum/Cultural building	CFD	People flow control	Caliendo et al. (2020)
	Owner, design	Religious building	SRA	Customisation of parameters	Naziris et al. (2016)
	Owner, design, user	Theater/Museum/Cultural building	CWS	Evacuation speed and time	D'Orazio et al. (2016)
	Owner, design	Residential/Multiuse building		Scenario, structure, installations, maintenance, propagation, and management	Shakib et al. (2018)
2. Update of measures	Owner, design	Residential/Multiuse building		Local rescue, lack of water and valuable artifacts	Kincaid (2019)
	Owner, design	Residential/Multiuse building		Materials, causes, history, codes and measures, with visual evaluation	Vijay and Gadde (2021)
	Owner, design	Castel/Palace			Kincaid (2018)
3. Fire protection assessment	Design, user	Theater/Museum/Cultural building		Static analysis and evaluation of fire resistance	Iringová and Idunk (2017)

(continued)

Table 2 (continued)

Study field	Target groups	Case study	Equipment	Indicators	References
	Owner, design, user	Residential/Multiuse building	CFD	Exposure to temperature and its evolution	Takács and Szikra (2017)
	Owner, design	Residential/Multiuse building		Physical, structural and layout determinants	Iringová and Vandličková (2019)
	Owner, design, user	Theater/Museum/Cultural building		Capacity load and safety	Quapp and Holschemacher (2020)
4. Material fire resistance	Design	Residential/Multiuse building	SAFIR	Vain, wood bending and fire exposures	Garcia-Castillo et al. (2021)
	Design	–		Mechanical and thermal properties	Daware and Naser (2021)
	Design	–	DRX e MEV	Compressive and bending resistance	Demircan et al. (2021)
	Owner, design, user	Residential/Multiuse building		FMC	Log (2016)
	Design	–	CFD	Fire resistance	Król (2016)
	Design	Religious building	FDS	ISO834 temperature–time curve	Shao and Shao (2018)
	Design	–		Microstructural development, diffraction and flammability analyses	Siligardi et al. (2017)
	Design	–		Carbonisation, ignition time and flame propagation	Chorlton and Gales (2019)

4 Discussion

The current systematic review focused on analysing fire tools and methodologies in historic buildings, with the primary objective of updating the studies carried out so far. In the analysis of the first research results, there was no strong link between the use of BIM/HBIM and fire safety in historic buildings. The main focus of the initial research, only 03 studies were found (Torero 2019; Bernardini et al. 2016; Frosini et al. 2016). Thus, the authors decided to eliminate BIM and HBIM, using

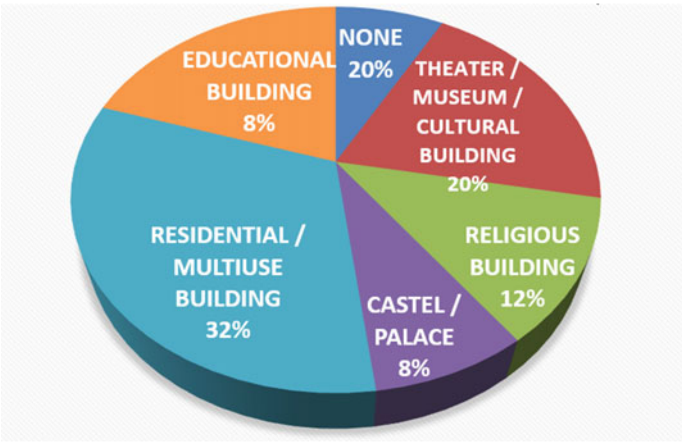

Fig. 4 Classification of articles based on the case study

the primary term "fire safety" only "historic buildings" (including "old buildings"), which resulted in more than 22 articles relevant to an investigation. The 25 selected articles were categorised into four studies with the same research objectives, as shown in Fig. 3. The following can be highlighted.

4.1 Group 1—Proposals for Improvements for Fire Safety in Historic Buildings

Among the ten articles in this research area, the most common indicators are related to the evacuation of buildings in three studies (Bernardini et al. 2016; Caliendo et al. 2020; D'Orazio et al. 2016) and the spread of fire in two studies (Chang et al. 2021; Tung et al. 2020)—see Table 2.

4.1.1 Evacuation of Buildings

The results revealed the evacuation of buildings as one of the most considered approaches to improvement proposals. Introducing low-impact components into the environment and an algorithm to assess possible overcrowding phenomena and identify the best evacuation routes can make up an Intelligent Evacuation Guidance System (Bernardini et al. 2016). To prevent an overcrowded museum, simulations verified the effectiveness of a noninvasive supplemental countermeasure based on an automatic system of control of the entry flow of people into the building (Caliendo et al. 2020). A system for evacuation guidance based on photoluminescent materials (PLM) has also been tested and approved, involving more than 100 people in smoke and darkness conditions (D'Orazio et al. 2016). The three proposals presented bring more solutions to achieve the evacuation of buildings to achieve better efficiency.

4.1.2 Fire Spread

Another approach considered more than once among the articles that presented proposals for improvements was related to the propagation of fire, and in both studies (Chang et al. 2021; Tung et al. 2020), the Software FDS—Fire Dynamics Simulator was used. To ensure that churches can be used in safer conditions, it is necessary to add active firefighting equipment initiated in wooden seats, for example (Chang et al. 2021). Numerical simulations that mimic the fire scenario compared to experiments in historical wood buildings on a real scale present development trends during fire spread (Tung et al. 2020). The perfecting of analysis tools related to the propagation of fire should be a continuous process and follow the development of new technologies because the result allows directing the interventions necessary to obtain greater safety more efficiently.

4.1.3 Other Results

Several studies propose features to improve the risk analysis process in historic buildings to achieve better fire safety. Appropriate tools to establish a proper performance assessment can result in minimal and rational changes that meet security goals while achieving other restoration goals (Torero 2019). To facilitate the process of analysis, design and fire management in historic buildings, automated procedures based on HBIM processes need to achieve interoperability with security software (Frosini et al. 2016). The use of parallel processing, combining the results of UFSM with SDS, improves the accuracy of fire risk models for cultural heritage buildings (Huang 2020). A tool based on heuristic meta optimisation can generate viable fund allocation solutions for different budget scenarios related to improving fire safety in historic buildings (Naziris et al. 2016). A risk reduction programme in an old building should assess different perspectives of progressive fire-induced collapse (Shakib et al. 2018).

4.2 Group 2—Updating Already Existing Measures

The three articles with research objectives related to this area (Kincaid 2018, 2019; Vijay and Gadde 2021) aim to include a broader target group, such as specialists, owners or users—see Table 2.

Not all historic buildings have many resources to apply to emergency planning, but even limited resources used with care can have a positive impact (Kincaid 2019). The preservation of historic buildings depends on use compatible with their structural and regular maintenance capabilities (Vijay and Gadde 2021). One of the critical factors in achieving robust fire safety is updating physical protection measures (Kincaid 2018). The measures already implemented are references to the new proposals, and updating this information is essential for both owners and specialists.

4.3 Group 3—Fire Protection Assessment

Among the four articles in this research area (Iringová and Idunk 2017; Takács and Szikra 2017; Iringová and Vandličková 2019; Quapp and Holschemacher 2020)—See Table 2, two points are worth mentioning and are related to each other: only one study used equipment to analyse their indicators (Takács and Szikra 2017), and all studies were focused on broader target groups including owners, users or specialists. A general assessment of the proposed systems for specific cases allows users and owners to familiarise themselves with the level of fire protection obtained in various buildings.

The optimisation of the planned function and its extension in the building allows the implementation of fire protection without further modifications to the original structures (Iringová and Idunk 2017). The protection cannot be omitted from the pillars until a certain height but can be left out in the carrying structure of the cover slab since the cover slab will not be in the flame zone of a possible fire show (Takács and Szikra 2017). Additional fireproof coatings must ensure Fire-resistance of the original structures if the extension in a cover space is made in places with low and medium fire load (Iringová and Vandličková 2019). Safety regulations and the protection of the historical structure should not be antagonistic but rather collaborate to preserve cultural heritage (Quapp and Holschemacher 2020).

4.4 Group 4—Resistance of Fire Material

In the case of the eight articles in this field (Garcia-Castillo et al. 2021; Daware and Naser 2021; Demircan et al. 2021; Log 2016; Król 2016; Shao and Shao 2018; Siligardi et al. 2017; Chorlton and Gales 2019), despite the different indicators analyzed, the most common studies are related to wood (Garcia-Castillo et al. 2021; Log 2016; Chorlton and Gales 2019) or masonry (Daware and Naser 2021; Demircan et al. 2021; Shao and Shao 2018). In these eight studies, the target groups mainly were specialists, except for (Log 2016), Table 2, and most of the articles (Daware and Naser 2021; Demircan et al. 2021; Król 2016; Siligardi et al. 2017; Chorlton and Gales 2019) did not use the Case Studies or assessment method to test their proposals.

4.4.1 Wood

Historical buildings do not always meet the requirements established by the standards and, therefore, the performance of analyses such as fire resistance of historical systems of wooden arched flooring is essential to ensure the preservation of architectural heritage (Garcia-Castillo et al. 2021). To reduce the likelihood of a fire outbreak, it can be predicted, for example, an increased risk associated with low CMF in inhabited wooden houses during winter (Log 2016). Historic wood chars at a rate up to 20% faster than contemporary wood, successful heritage conservation efforts by leaving wood exposed and on-site become possible once the wood performance is understood and other fire safety engineering strategies are in place (Chorlton and Gales 2019).

4.4.2 Masonry

Modern and updated temperature-dependent material models facilitate the design of new masonry constructions or the analysis of existing ones, including historic buildings (Daware and Naser 2021).

Mortars produced based on hydraulic lime have their mechanical properties affected when exposed to high temperatures. For the integrity of historic buildings, it would be more appropriate to use flyash (FA)—30% and granulated blast slag (GBFS)—15% (Demircan et al. 2021). In a fire in historic buildings, the cracks of the damaged, exposed side of the brick walls or the ineffectiveness and cracks of the fireproof material used are responsible for the expansion of smoke and combustion (Shao and Shao 2018).

4.4.3 Other Results

To properly evaluate the safety of steel beam floors with beams hidden in the thickness of the slab, it is necessary to treat each design case individually when assessing the fire conditions due to significant discrepancies found in final results (Król 2016).

The fibre-reinforced aerogel is a state-of-the-art, fire-resistant material suitable for replacing traditional ones such as rock wool, especially for retrofit and renovation of historic buildings, where interior insulation may be the only alternative (Siligardi et al. 2017).

4.5 Future Research Perspectives

The different studies addressed in this review evidenced the research trends on areas involving measures of improvement and resistance of fire material. While research on fire safety in historic buildings has been evolving, limitations were found in the number of approaches related to the use of BIM or HBIM. Some studies have highlighted the need to improve interoperability with fire safety software, use parallel processing, and create extensions of analysis tools to improve the accuracy of your simulations and reduce the margin of error. In addition, most investigations performed their analyses through a case study, which showed that using larger samples might also be the focus of future research.

Finally, there is a tendency for studies involving improvement measures and resistance of fire material to promote fire safety in historic buildings. Future prospects should explore the potential for management and dissemination of information through the use of BIM or HBIM and in larger samples during real-life operations.

Limitations
The possible deletion of some articles due to the non-compliance with some criteria applied, such as English language and search publication, may have left out data sources. In addition, given the variety among the studies, it was necessary to perform a statistical analysis combining the research areas for a clearer understanding of the results. The definition of these may have disregarded specific points relevant to some articles.

5 Conclusions

About the possibility of obtaining the information about the building and managing it, in a single location, with different disciplines, there are many advantages in using HBIM in historic buildings. However, no articles were explicitly found focusing on the application of HBIM for fire safety in historic buildings. Despite the various approaches found for fire safety, most studies focused on material improvements and fire resistance. Moreover, including the trend of growth of these approaches in recent years, the results allow us to validate the need for continuity and deepening on the theme, to promote the integration and optimisation of information of the heritage built through the use of HBIM to understand the past, present better and provide the tools for the safe future of historic buildings.

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