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# Fire in heritage and historic buildings, a major challenge for the 21st century

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ABSTRACT

Heritage and historic buildings possess an important architectural and cultural value which fire significantly threatens. However, current codes very rarely address the peculiarities of such buildings vis-à-vis fire hazards. Therefore, bringing these buildings into compliance with fire safety regulations while avoiding heritage loss is a great challenge. Within this context, this study provides a comprehensive overview of the current state of the art of research on fire in heritage and historic buildings. The analysis of the literature shows that, despite significant advances in research, the fire safety of historic buildings remains alarming, with important research gaps to be addressed. This study identifies these gaps, proposes future research areas, and provides a baseline for the search for solutions to achieve fire safety in heritage and historic buildings. Thus, this work promotes the conservation of these buildings, as well as rehabilitation over demolition and new construction, leading to a more sustainable construction.

## 1. Introduction

Heritage or historic buildings are those considered to be of great architectural or historic value, those located in conservation areas, or those whose traditional form and construction give them a special interest (HM Government, 2015). In many countries, those of particular significance are listed in registers of historic places to ensure their protection and preservation. The National Register of Historic Places in the United States, the National Heritage List for England, and the "Registro de Bienes de Interés Cultural" in Spain are just a few examples of heritage registers that exist in different countries around the world. Likewise, the UNESCO World Heritage List includes historic buildings that, because of their importance and uniqueness, should be internationally recognized. In short, historic buildings are a major asset of our civilization and international organizations such as ICOMOS (International Council on Monument Sites) and the United Nations through the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2015) focus their efforts on promoting the conservation of built heritage.

However, fire is a major threat to achieve heritage preservation, as well as an important agent of urban transformation. Throughout the ages, notable fires around the world, such as the Great Fire of Rome in 64; the Great Fire of London in 1666; the three major fires in New York City in 1776, 1835 and 1845; and the Great Chicago Fire in 1871; had devastating effects and forced the reconstruction of a large part of those cities. Heritage and historic buildings were designed when modern fire engineering standards did not exist. Consequently, they generally do not meet the requirements of current regulations. This fact, added to other fire hazards frequently encountered in historic buildings (e.g., the presence of high fire loads, their proximity to surrounding buildings facilitating fire spread, and the difficulty for fire emergency services to access historic city centers where they are often located), makes them especially vulnerable to fire. As a result, fire has ravaged numerous historic buildings (e.g., the Windsor Castle in England in 1992 (Utt, 2013), the National Museum of Brazil in Rio de Janeiro in 2018 (Brazil's national museum hit by, 2018) and the Notre Dame in Paris, France, in 2019 (Astier, 2019)) and, in some cases, even entire historic neighborhoods (e.g., the Chiado fire in Lisbon, Portugal, in 1988 (Neves et al., 1995) and the fire in the city of Funchal, on the Portuguese island of Madeira, in 2016 (Madeira wildfires, 2016)). It is important to note that, in these cases, the heritage loss is not only the building itself and its fabric, but also its contents, such as furnishings and works of art, which cannot be replaced. Besides the importance of heritage conservation, the rehabilitation and reuse of historic buildings also contributes to more sustainable construction. More specifically, compared to demolition and new construction, rehabilitation involves lower environmental impact

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(Alba-Rodríguez et al., 2017; Gaspar and Santos, 2015), as existing resources are reused and less construction waste is generated. However, rehabilitation requires adapting the performance of existing buildings to meet current code requirements, including fire safety. Still, current fire codes do not generally contemplate specific guidelines or methods for historic buildings. Thus, bringing them into compliance with current fire safety regulations following typical prescriptive approaches very often requires massive and detrimental interventions that diminish their architectural value or, when fire safety requirements cannot be met, results in total or partial demolitions. Summarizing, addressing fire safety in historic buildings is a difficult task since it entails finding the right balance between achieving an adequate level of fire safety and ensuring heritage preservation and sustainability. Consequently, the adoption of particular strategies (e.g., performance-based approaches) on a case-by-case basis is essential.

Within this context, the aim of this review paper is to provide a comprehensive overview of the current state of the art of research on fire in historic buildings, as well as to identify knowledge gaps that need to be addressed. Consequently, it is intended to be used as a baseline for the search for solutions to the threat posed by fire to these buildings, thereby promoting heritage preservation and sustainability. For this purpose, an exhaustive literature review was conducted, knowledge gaps were determined based on a statistical analysis and, finally, future research areas were proposed. Thus, hereinafter, the paper is structured as follows. Section 2 mainly describes the methodology followed to carry out the search and selection of studies for the literature review. Section 3 presents a general analysis of the search results, followed by a series of subsections, each associated with a specific topic or research field, in which the main contributions are described. Next, Section 4 provides a general discussion on the state of the art based on the selected studies and includes the results of the statistical analysis, as well as the aspects that should be addressed in future research. Lastly, Section 5 summarizes the main conclusions of this review paper.

## 2. Methodology

The search for studies related to fire in historic buildings was carried out mainly through the Scopus bibliographic database. In this case, the search strategy in Scopus consisted of collecting all those studies whose title, abstract or keywords contained at least one term from each of the two sets of terms considered. Thus, the Boolean operator used in the search to connect the terms of the same set was "OR", whilst the one used to combine terms from different sets was "AND". The first set included the terms "fire" and "fire engineering", whereas the second set contained the terms "historic(al) building(s)", "heritage building(s)", "historic(al) structure(s)" and "heritage structure(s)". Note that the letters in parentheses in some of the terms of the second set refer to alternatives to those terms, which were also assumed in the search. Therefore, a total of 24 possible term combinations (TC) were used as input to conduct the search, which are listed in Table 1. Note that each term combination contains one term from each of the two sets of terms considered. In addition, to narrow down the results, the search was limited to peer-reviewed journal articles and conference proceedings written in English. It is important to highlight that no specific search period was established.

After analyzing the search results, a filtering process to select those studies relevant to the subject under consideration was performed. To avoid the omission of any important publication, Google Scholar and Web of Science bibliographic databases were subsequently used to complement the Scopus search results. Once the search and selection processes were completed, the studies were classified into different research fields according to the topics, issues or challenges they address in order to finally conduct a statistical analysis, namely a simple correspondence analysis, to identify knowledge gaps within the scope of this study. It is worth noting that a total of 125 studies were selected from the bibliographic databases considered. Fig. 1 summarizes the methodology followed in the literature review conducted in the present study.

## 3. Results

### 3.1. General overview

First, a bibliometric analysis of the keywords of the Scopus search results was carried out using the VOSviewer software (van Eck and Waltman, 2010). This type of analysis is useful to assess which are the most researched topics within a field and the connections between them, as well as to determine possible knowledge gaps. Note that this methodology has been applied in recent literature review papers (Fernández-Mora et al., 2022; Adegoriola et al., 2021). In this case, only those keywords found in more than 5 studies were considered in the analysis. In addition, it should be noted that keywords with equivalent meanings were grouped together to facilitate the visualization of the map. Thus, a total of 54 keywords met the threshold. Fig. 2 shows the keyword map obtained from the analysis. Note that the color of the circle next to each keyword represents the average publication year of the studies containing it. Regarding the interpretation of the map, the higher the size of the circle, the greater the number of co-occurrences of the keyword and, generally, the closer the circles are to each other, the stronger their relatedness. The latter is also represented by the lines connecting the

**Table 1**
Combinations of terms used as input to perform the search in Scopus.

| | |
|---|---|
| TC-01: "fire" AND "historic building" | TC-13: "fire engineering" AND "historic building" |
| TC-02: "fire" AND "historic buildings" | TC-14: "fire engineering" AND "historic buildings" |
| TC-03: "fire" AND "historical building" | TC-15: "fire engineering" AND "historical building" |
| TC-04: "fire" AND "historical buildings" | TC-16: "fire engineering" AND "historical buildings" |
| TC-05: "fire" AND "heritage building" | TC-17: "fire engineering" AND "heritage building" |
| TC-06: "fire" AND "heritage buildings" | TC-18: "fire engineering" AND "heritage buildings" |
| TC-07: "fire" AND "historic structure" | TC-19: "fire engineering" AND "historic structure" |
| TC-08: "fire" AND "historic structures" | TC-20: "fire engineering" AND "historic structures" |
| TC-09: "fire" AND "historical structure" | TC-21: "fire engineering" AND "historical structure" |
| TC-10: "fire" AND "historical structures" | TC-22: "fire engineering" AND "historical structures" |
| TC-11: "fire" AND "heritage structure" | TC-23: "fire engineering" AND "heritage structure" |
| TC-12: "fire" AND "heritage structures" | TC-24: "fire engineering" AND "heritage structures" |

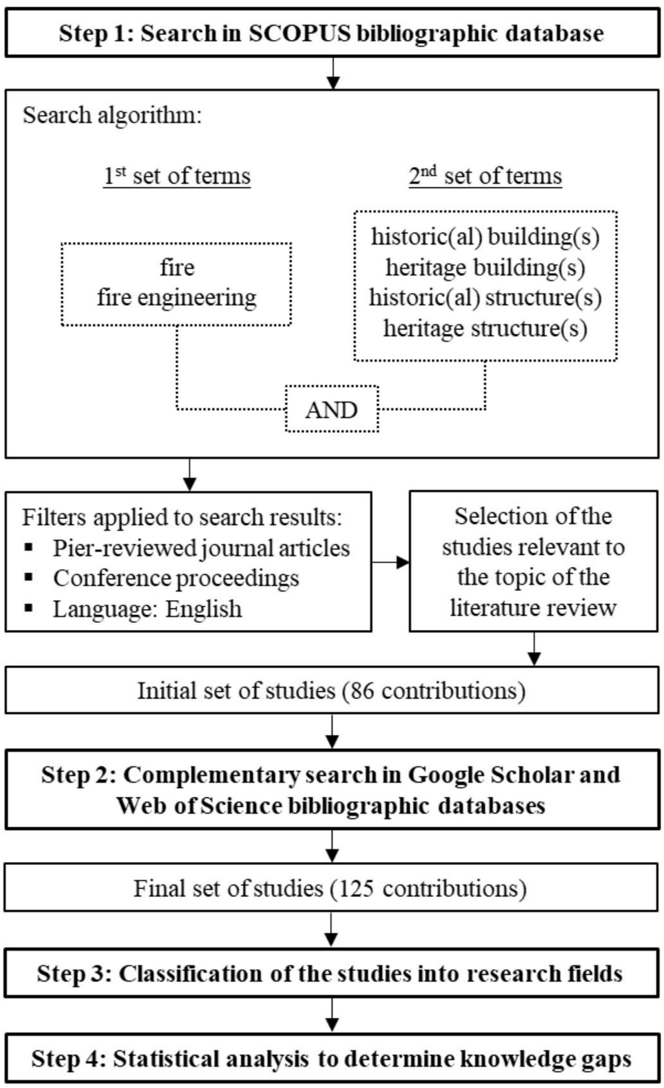


**Fig. 1.** Flowchart describing the methodology adopted for the literature review.

most closely associated keywords.

As can be observed in Fig. 2, the keywords "fire", "historic buildings" and "heritage buildings" are among the most frequent, since they coincide with some of the terms considered in the bibliographic search. Other common keywords are "fire protection", "fire safety", "fire resistance", "architectural heritage", "cultural heritage", "heritage preservation" and "timber". According to Fig. 2, the earliest studies seem to focus on fire protection and mitigation measures for historic buildings, as evidenced by the average publication year of studies with keywords such as "fire protection", "smoke detectors", "water mist systems", "personnel", and "risk management". In the same vein, the "fire risk assessment" of historic buildings was also a recurring topic. It should be highlighted that fire risk analyses are essential to mitigate the fire risk (i.e., the probability of occurrence and the severity of the consequences) that can compromise the preservation of historic buildings. These analyses consist of identifying potential fire hazards, assessing the probability of occurrence and consequences of those hazards, and adopting the most appropriate fire safety strategy (Watts and Hall, 2016). Among the most frequent fire risks in historic buildings are the presence of a large amount of potential fuel, the vulnerability to ignition and fire spread, and non-compliant means of escape (Kincaid, 2022; Bernardini, 2017; Gales et al., 2022).

In later studies, heritage preservation awareness started to gain more importance and keywords such as "maintenance", "restoration" and "reinforcement" are aligned with that purpose. More recent research seems to be directed towards the study of the thermal and thermo-mechanical behavior and fire resistance of historic building materials and, consequently, of existing historic structures. In particular, the keyword group constituted by "high temperature", "rock mechanics" and "compressive strength" can be associated with research on the thermal and thermomechanical behavior of historic masonry structures, whilst keywords such as "timber structures", "wooden buildings" and "timber" are closely related to the keyword "fire resistance". Moreover, "sustainability" is a relevant aspect that is also being considered in recent studies. In short, a clear transition can be appreciated from, initially, the concern to protect historic buildings from fire regardless of the impact on their aesthetics towards, at present, the desire to preserve the built heritage while achieving fire safety by assuming fire safety engineering approaches.

As stated in the previous section, after analyzing the search results from the three different bibliographic databases considered, a total of 125 studies published between 1985 and 2022 were selected to be included in the literature review. It should be noted that, among the search results, a literature review on research on fire protection in historic buildings by Huang et al. (2009) and published in 2009 was found. However, it does not include many of the selected studies published before 2009. Therefore, all these studies were included in the present literature review to get a comprehensive perspective. Concerning the 125 selected papers, Fig. 3 shows the number of studies published per year, as well as the cumulative number over the years. As can be deduced, the topic has gained attention in recent years and a general trend towards an increase in the number of studies published annually can be observed. In fact, almost 60% of the studies are concentrated between 2016 and 2022. This growing interest could be explained by the alignment of the topic with the 11th and 12th Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2015) approved by the United Nations in 2015. More specifically, one of the targets of the 11th SDG is to "strengthen efforts to protect and safeguard the world's cultural and natural heritage", which obviously requires the protection of the heritage vis-à-vis fire hazards. On the other hand, the refurbishment and reuse of heritage buildings also contribute to the fulfillment of some of the targets of the 12th SDG, namely to "achieve the sustainable management and efficient use of natural resources" and to "substantially reduce waste generation through prevention, reduction, recycling and reuse". It is important to highlight that the number of studies published in 2022 is lower than in previous years. However, it can be expected to increase throughout the year.

Finally, the selected studies were classified according to 6 different main research fields: (1) fire safety regulations (Papaioannou, 1985; Marchant, 1989; Torero, 2019a, 2019b; Quapp and Holschemacher, 2020; Beilicke, 1991; Malhotra and Papaioannou, 1991; Pickard, 1994a, 1994b; Watts, 2001; Watts and Solomon, 2002; Phillips, 2010; Morrison and Hamre, 2018); (2) fire risk assessment (Watts and Kaplan, 2001; Copping, 2002; An and Liu, 2013; Arborea et al., 2014; Mydin et al., 2014; Othuman Mydin et al., 2014a, 2014b; Hardie et al., 2014; Xu et al., 2015; He and Park, 2017; Akashah et al., 2016; Liu et al., 2019; Akinciturk and Kilic, 2004; Li and Deliberty, 2021; Du and Okazaki, 2016; Du et al., 2017; Yuan et al., 2018; Brimblecombe et al., 2020; Tozo Neto and Ferreira, 2020; Li et al., 2021; Granda and Ferreira, 2021; Salazar et al., 2021; Salleh and Ahmad, 2009; Ibrahim et al., 2011a, 2011b; Durak et al., 2011; Biao et al., 2012; Martokusumo et al., 2013; Himoto and Nakamura, 2014); (3) fire protection and mitigation measures (You et al., 2011; Porter et al., 1998; Dong et al., 2014; Kim et al., 2015; Zhang et al., 2015; Holschemacher and Quapp, 2019; Naziris et al., 2016a, 2016b; Marrion, 2016; Kincaid, 2012, 2018, 2019, 2020, 2021; Guan et al., 2018; Nieuwmeijer, 2001; Devi and Sharma, 2019; Zahmatkesh and Memari, 2017; Salleh and Mohtar, 2020; Vijay and Gadde, 2021; Venegas et al., 2021; Doulgerakis et al., 2021; Bakas et al.,

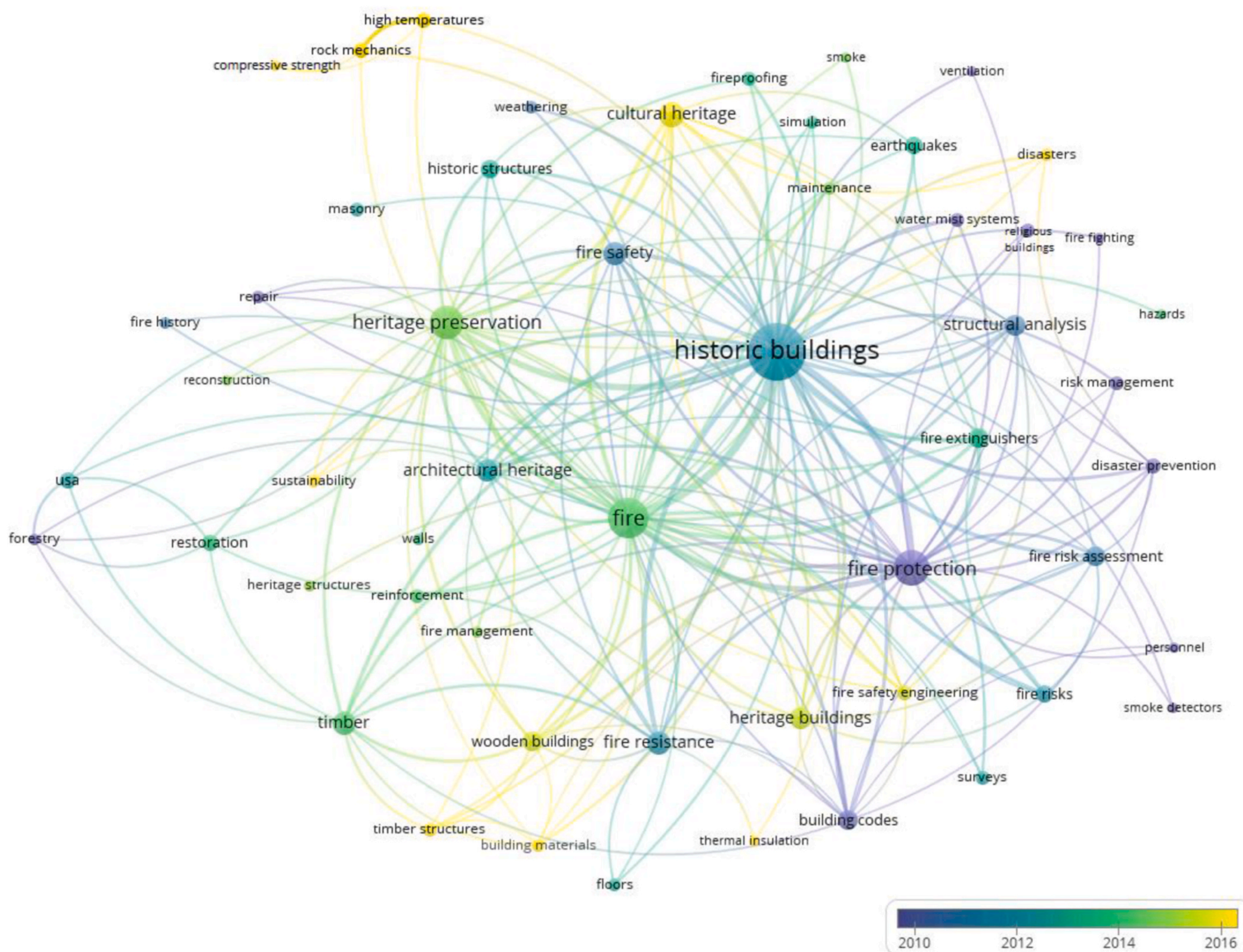


**Fig. 2.** Keyword map of the Scopus search results (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.).

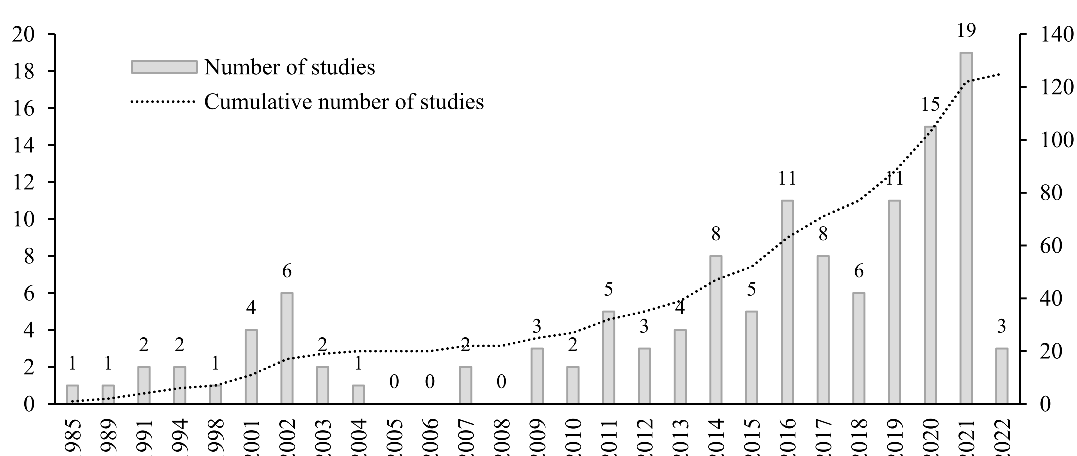


**Fig. 3.** Number of studies published per year and cumulative number over the years.

2020; Fan, 2001; Aiello et al., 2002; Lercari et al., 2021; Kaplan, 2003; Xiaomeng et al., 2010; Kupilík et al., 2013); (4) spread of both fire and smoke and evacuation (Hasemi et al., 2002a; Peng et al., 2011; Tung et al., 2020; Huai et al., 2021; Manuello Bertetto et al., 2021; Zhou et al., 2021; Cao et al., 2021; Lena et al., 2012; Chen et al., 2015; Bernardini et al., 2016; D'Orazio et al., 2016; Caliendo et al., 2020; Yang et al., 2022; Suzuki and Manzello, 2019; Cao et al., 2020); (5) thermal and thermomechanical behavior of historic structures or materials (Hasemi

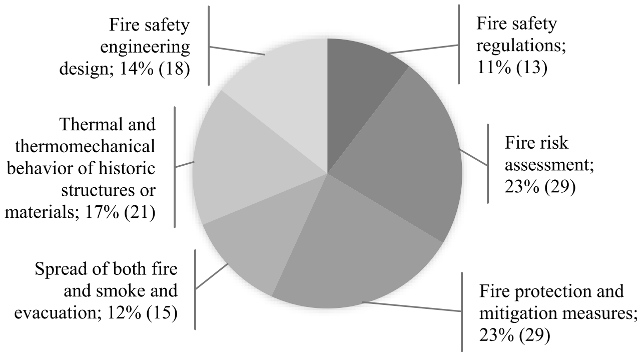


**Fig. 4.** Percentage and number of studies per research field.

et al., 2002b; Gomez-Heras et al., 2009; Pachta et al., 2018, 2021; Garcia-Castillo et al., 2021; Demircan et al., 2021; Vasanelli et al., 2021; Liblik et al., 2021; Shao and Shao, 2018; Chorlton and Gales, 2019, 2020; Zhou et al., 2019; Kielė et al., 2020; Maraveas et al., 2013, 2014, 2015, 2016a, 2016b, 2017; Otto et al., 2017; Garrido et al., 2022); and (6) fire safety engineering design (Wouters and Mollaert, 2002, 2003; Claret and Andrade, 2007; Iringová and Idunk, 2017; Pau et al., 2019; De Medici et al., 2019; Petrini et al., 2022; Chang et al., 2021; Miano et al., 2020; Węgrzyński et al., 2020; Li et al., 2020; Tsui and Chow, 2007; Bukowski and Nuzzolese, 2009; Frosini et al., 2016; Król, 2016; Su et al., 2020; Takács and Szikra, 2017; Szumigała and Polus, 2017). Fig. 4 shows the percentage of studies associated with each category, as well as the corresponding number of studies in parenthesis. A general overview of the studies by research field is provided in sections 3.2 to 3.7 below.

### 3.2. Fire safety regulations

One of the first guidance documents on fire safety in historic structures to appear was the *NFPA 914 – Recommended Practice for Fire Protection in Rehabilitation and Adaptative Reuse of Historic Structures*, which was published in 1989 and developed by the Technical Committee on Cultural Resources of the American National Fire Protection Association (NFPA). This committee was set in 1940 as the Committee on Libraries, Museums, and Historic Buildings. NFPA 914's 1989 edition was based on the manual *Protecting our Heritage: Historic Buildings, Museums, and Libraries* (Committee on Libraries, 1948) developed by the committee and published in 1948. However, it is NFPA 914's 2001 edition, entitled *Code for Fire Protection of Historic Structures*, the one that marked a turning point. Thus, Watts and Solomon (2002) and Watts (2001) focus on a detailed description of this code. NFPA 914's 2001 edition was the first American model code that regulated fire safety in heritage buildings (Watts and Solomon, 2002), replacing previous editions of NFPA 914, which were recommended practices and, therefore, not enforceable documents. The 2001 edition of NFPA 914 was developed based on the idea that a prescriptive solution is not always applicable due to the uniqueness of the historic structures. Furthermore, as stated by Watts (2001), prescriptive approaches to meet fire and life safety objectives can sometimes seriously compromise the historic or architectural value of the historic building. Therefore, in addition to including prescriptive approaches, the innovation of this code was the introduction of performance-based approaches through the definition of goals, objectives and performance criteria to achieve acceptable levels of protection regarding fire safety in historic buildings (Watts, 2001) as a more flexible alternative. Finally, NFPA 914's 2001 edition also included a process to analyze the fire safety needs in historic buildings. Note that NFPA 914's current edition is 2019 (Technical Committee on Cultural Resources, 2019) and that, unlike current structural fire safety regulations, whose primary objective is to ensure the life safety of occupants, NFPA 914 also aims to protect historic buildings and their contents and fabric.

In Europe, awareness of fire safety in historic buildings began to grow in 1987, when the Conseil International du Bâtiment (CIB), currently known as International Council for Research and Innovation in Building and Construction, raised the issue in the CIB W14 Fire Commission, following a visit by some of its members to heritage buildings in Mount Athos, Greece. This visit generated great concern for the preservation of historic monuments and buildings, and the preliminary study conducted after it by Papaioannou (1985) in 1985 proposed the first guidelines that might be helpful for fire safety design of historic buildings. Note that this study is the oldest of those included in the literature review and, consequently, is one of the first studies to show concern for the issue. At the 1987 meeting, CIB W14 agreed that heritage buildings frequently present a high fire risk and decided to create a working group to study the fire safety issues and to develop a CIB guide on fire safety for heritage buildings. For that purpose, Malhotra and Papaioannou (1991) prepared a framework for the guide covering fire safety aspects such as evaluation of the hazard, potential measures to prevent fires, life safety, fire damage minimization and post fire activity. In addition, this guide's outline acknowledged the importance of adopting fire safety engineering approaches in historic buildings instead of following rigid prescriptive requirements. Likewise, Beilicke (1991) listed for CIB W14 the issues and potential risks that can be encountered when dealing with fire safety of heritage buildings and also stated that the best way to overcome those problems is working cooperatively with construction, restoration, building fire protection and fire brigade experts. Based on these works, CIB W14 identified the development of a "guidance document on rational fire safety engineering approach to fire safety in historic buildings" as a high-priority project within the commission (Watts, 2001).

Thus, by the late 1980s, signs of concern for fire safety in historic buildings in Europe were already evident. However, as reported by Marchant (1989), the lack of specific guidance to address fire safety in historic buildings was jeopardizing their preservation. Moreover, Marchant (1989) also suggested that fire safety should be based on fire engineering approaches, whose solutions reduce the fire risk to an acceptable level, instead of on rigid prescriptive solutions. Historically, building regulations in many countries around the world tended to propose prescriptive approaches. Prescriptive building codes made it very difficult to meet the requirements whenever a historic building was refurbished or its use changed, as they do not allow any flexibility in achieving them. Consequently, this situation had an enormous impact in the architectural heritage of many countries, since many historic buildings were lost to build new ones or were aesthetically damaged (Torero, 2019a, 2019b). In the face of growing concern about this issue between preservation and fire safety, more flexible regulations began to appear in Europe. For instance, Pickard, 1994a, 1994b, who analyzed the fire safety legislation and the fire safety engineering considered in England and Ireland until the mid-1990s, noted the advance introduced by the 1991 Building Regulations of England in allowing certain requirements to be waived if compliance with the regulations was unacceptable regarding the preservation of the historic building (Pickard, 1994b).

In recent years, similar documents have been published describing current fire safety regulations of different countries that are applicable to historic buildings, as well as the associated problems or limitations. Phillips (2010) and Quapp and Holschemacher (2020)), focusing on Australian and German codes, respectively, highlighted the difficulties in satisfying both heritage preservation interests and fire safety aspects. The lack of applicability of the methods of current fire safety regulations to historic buildings (Quapp and Holschemacher, 2020), as well as the large number of requirements that must be met (Phillips, 2010), are just a few examples of the worrying situation that historic buildings still face. Torero, 2019a, 2019b raised similar issues and emphasized that performance-based approaches are necessary to achieve an adequate level of fire safety with minimal impact on the historic and architectural value of buildings. Thus, a framework of analysis to assess whether historic buildings meet fire safety objectives was presented. Finally, Morrison and Hamre (2018) recently offered their point of view based on their professional experience in projects related to historic buildings in Canada. In the absence of specific fire safety provisions for heritage building in the Canadian building code, Morrison and Hamre (2018) complement it with the NFPA 914 to achieve fire safety in those buildings.

In short, the problems related to fire safety regulations in historic buildings reported in recent studies (Torero, 2019a, 2019b; Quapp and Holschemacher, 2020; Phillips, 2010; Morrison and Hamre, 2018) are not very different from those noted in older ones (Marchant, 1989; Malhotra and Papaioannou, 1991; Watts, 2001). This fact is worrisome, as it denotes that insufficient attention has been paid to solving the issues. In any case, all these studies (Marchant, 1989; Torero, 2019a, 2019b; Quapp and Holschemacher, 2020; Malhotra and Papaioannou, 1991; Watts, 2001; Phillips, 2010; Morrison and Hamre, 2018) concur that fire safety solutions for historic buildings should be based on performance-based approaches to ensure both fire safety and heritage preservation.

### 3.3. Fire risk assessment

#### 3.3.1. Fire risk indexes

The literature collected includes different studies that propose indexes to quantify the fire risk level of historic buildings (Watts and Kaplan, 2001; Copping, 2002; Arborea et al., 2014; Ibrahim et al., 2011a). These fire risk indexes can be also helpful for the decision-making process of fire safety design alternatives, if required, to improve fire safety performance of historic buildings.

First, Watts and Kaplan (2001) developed the Historic Fire Risk Index (HFRI), which is a fire risk-indexing system focused on historic house museums and based on the evaluation of multiple attributes such as fire prevention, building significance, fire growth rate and emergency response. From its application, a single numerical value that represents the level of fire safety of the historic building evaluated is obtained as a result of the summation of each fire safety attribute's weight times the attribute's grade or degree of danger. Both the fire safety attributes and the corresponding weights were based on two well-established fire risk-indexing systems widely used for life safety evaluation in the United States, FSES (NFPA 101A: Guide on Alternative Approaches to Life Safety, 1998) and BOCA (The BOCA National Building Code, 1996). On the other hand, Copping (2002) developed a decision-making tool, referred to as Fire Safety Evaluation Procedure for the Property Protection of Parish Churches [Fire(SEPC)], to determine whether or not a particular parish church is within an acceptable level of fire safety considering the vulnerability and value of its fabric and contents. Basically, the evaluation system consisted of two different survey-based assessments of: (1) the existing fire safety in the church using a hierarchical framework that evaluates 18 fire safety components, and (2) the vulnerability of the church to fire through a vulnerability logic map. Similarly, Ibrahim et al. (2011a), based on the requirements of Malaysian building codes, elaborated a survey questionnaire for on-site evaluation of heritage buildings in Malaysia, from which a fire risk index is obtained as a result. In this case, the fire safety attributes to be assessed through the survey were selected from a literature review, while the weighting values were set by a panel of experts who ranked the attributes according to their importance in fire safety. Arborea et al. (2014) proposed a Fire Risk Index Method for Historical Buildings (FRIM-HB) with the aim of integrating fire risk to the "Italian Risk assessment map of the cultural heritage", which is a platform based on a geographic information system (GIS) to study the vulnerability of built heritage to static-structural, environmental, anthropogenic, and seismic risks. Basically, the FRIM-HB is a fire risk index that includes twenty-three fire safety attributes to be assessed in situ for the heritage building under consideration and whose relative contribution to the index was established by a panel of experts. Finally, Salazar et al. (2021) recently conducted a comprehensive review of available fire risk indexes that can be used to assess the vulnerability of existing cultural heritage. A total of twenty-two indexes, which address different aspects of fire risk; namely, building features, utilities, fire protection measures, and fire emergency preparedness, were presented. The applicability of these indexes to different types of cultural heritage (e.g., buildings, towers, historic centers, archaeological sites, bridges, statues, etc.) was also discussed.

Note that, although other studies collected from the literature consider alternative fire risk indexes (Yuan et al., 2018; Tozo Neto and Ferreira, 2020; Granda and Ferreira, 2021), these have been included in the following section, since they do not aim to propose a fire risk index, but to show the application of an existing one to a case study.

#### 3.3.2. Case studies assessing the fire risk

This section gathers the studies found in the literature that contemplate qualitative (An and Liu, 2013; Mydin et al., 2014; Othuman Mydin et al., 2014a, 2014b; Hardie et al., 2014; Xu et al., 2015; Akashah et al., 2016; Liu et al., 2019; Akinciturk and Kilic, 2004; Du and Okazaki, 2016; Du et al., 2017; Li et al., 2021; Salleh and Ahmad, 2009; Durak et al., 2011; Biao et al., 2012; Martokusumo et al., 2013), quantitative (Li and Deliberty, 2021; Yuan et al., 2018; Brimblecombe et al., 2020; Tozo Neto and Ferreira, 2020; Granda and Ferreira, 2021), or probabilistic (He and Park, 2017; Himoto and Nakamura, 2014) approaches to assess the fire risk of cultural heritage, including buildings, villages and historic city centers.

According to the literature, fire risk of historic buildings appears to be a major issue, particularly in Malaysia (Mydin et al., 2014; Othuman Mydin et al., 2014a; Othuman Mydin et al., 2014b; Akashah et al., 2016; Salleh and Ahmad, 2009; Ibrahim et al., 2011b) and China (An and Liu, 2013; Xu et al., 2015; Biao et al., 2012). First, with regard to Malaysia, Salleh and Ahmad (2009) surveyed thirty seven heritage buildings currently used as museums to analyze their fire safety management. Othuman Mydin et al. examined, through on-site inspections and interviews with building owners and staff, the potential fire hazards as well as the implemented fire emergency plans in heritage shop houses whose use was changed to sleeping accommodations (Mydin et al., 2014) and ancestral temples (Othuman Mydin et al., 2014a, 2014b) in Penang, Malaysia. Finally, Akashah et al. (2016) evaluated the fire risk status of historic museums in Malacca, Malaysia, to propose a fire safety planning for historic buildings. Overall, these studies showed that most heritage buildings in Malaysia still have poor fire safety management, limited fire safety measures and, therefore, high fire risk. Furthermore, the conservation of Malaysian heritage buildings, as well as their features and contents, has so far not been prioritized. The latter was evidenced in the study conducted by Ibrahim et al. (2011b), which gathered the perspectives of different parties involved in the fire safety management of heritage buildings in Malaysia, placing this aspect as the least relevant when addressing the fire safety of heritage buildings. Therefore, the lack of awareness on heritage preservation, together with the lack of legislations or guidelines on fire safety for heritage buildings (Salleh and Ahmad, 2009), seriously threaten the conservation of the architectural and cultural values of heritage buildings in Malaysia.

In the case of China, An and Liu (2013) described the widespread and alarming situation of historic buildings regarding fire safety and provided prevention and control strategies. Similarly, Xu et al. (2015) examined the deficiencies in disaster prevention and mitigation in architectural heritage areas in China, and studied the potential impacts that common disasters, including fires, can cause on built heritage. The study also discusses the factors that should be considered when assessing the risk associated with each disaster, as well as disaster prevention and mitigation strategies. Lastly, with a more specific approach, Biao et al. (2012) conducted a fire hazard survey of Group-living Yards belonging to the cultural heritage of Tianjin, China, and found that the fire risk of these sites is worrying. Consequently, fire protection measures to improve the fire safety of these historic buildings were proposed, and their effectiveness in a Group-living Yard used as case study was verified through a computational fluid dynamics (CFD) model built with the software Fire Dynamics Simulator (FDS).

Similar studies on the fire risk of historic buildings in other countries have also been conducted. As already discussed for other Asian countries, Indonesian heritage buildings have poor fire safety management, along with inadequate or insufficient fire safety equipment, and face challenges such as the lack of awareness and fire safety regulations (Martokusumo et al., 2013). Thus, the fire risk assessment of two historic buildings on a university campus in Indonesia carried out by Martokusumo et al. (2013) revealed the urgency of implementing reliable fire safety management to meet both fire protection and heritage preservation. In the same way, the surveys conducted by Hardie et al. (2014) to identify structural fire hazards due to non-compliances with current building regulations in a 19th century heritage housing stock in Sydney, Australia, showed that most of the heritage buildings exhibited multiple fire risk factors. Moreover, He and Park (2017), based on the study by Hardie et al. (2014), used a statistical approach to estimate the probabilities of occurrence of those fire hazards, and developed logistic regression models to correlate them. Results showed significant correlations between some of the structural fire hazards, as well as high probabilities of finding at least one or multiple hazards in the analyzed heritage housing stock in Sydney.

On the other hand, the literature also reflects great concern about the fire risk of historic villages (Liu et al., 2019; Akinciturk and Kilic, 2004; Du and Okazaki, 2016; Du et al., 2017; Yuan et al., 2018; Li et al., 2021; Durak et al., 2011), especially in China (Liu et al., 2019; Du and Okazaki, 2016; Du et al., 2017; Yuan et al., 2018), where these settlements are still common. First, Liu et al. (2019) provided an overview of the fire hazards frequently encountered in rural historic buildings in the southern region of China and, consequently, of the worrying fire safety situation of its traditional villages and settlements. In the same vein, Yuan et al. (2018) employed the fire risk index developed by Watts and Kaplan (2001) to quantify the fire safety level of the Dangjia village in China based on the multiple fire hazards that were identified from an on-site inspection. As a result, a low fire safety level was obtained, which implies a high vulnerability of the heritage village to fire. Besides the fire safety issues that historic buildings typically face, these villages are often located in remote areas that are difficult for fire emergency services to access and their sparse population makes the establishment of independent fire brigades unfeasible. In such a case, the cooperation of their inhabitants in providing a first response in a fire can be decisive in many cases. For this reason, Du et al. (Du and Okazaki, 2016; Du et al., 2017), in a more specific context, assessed the community fire coping capacity of a historic dong village in Guizhou, China. Although findings from the surveys conducted showed the willingness of its inhabitants to cooperate, issues such as the lack of an integrated fire risk reduction planning and the lack of fire safety knowledge seriously jeopardize the preservation of the village in case of fire. Historic villages in Japan, which are often located in remote mountainous areas, confront similar problems. Thus, Li et al. (2021) recently assessed the fire safety issues of Hanazawa historic mountain village, and then proposed a fire safety planning based on the cooperation and firefighting aptitudes of local residents. Finally, although the study is not very recent, the study carried out by Akinciturk and Kilic (2004) on the fire risk status of the historic Cumalıkızık village, an Ottoman settlement in Bursa, Turkey, had a great repercussion in making the local authorities conscious of the severity of the situation, and fire prevention strategies were implemented shortly after. Furthermore, this study led to the one conducted by Durak et al. (2011), whose main objective was to raise awareness of the urgency of addressing the fire risk problem in Misi Village, which is a traditional settlement located in the same city, to ensure its preservation. For that purpose, the fire hazards of Misi village were identified, concluding that the implementation of fire protection measures combined with the cooperation of local authorities and the local community were essential.

Overall, as reported in the previous studies (An and Liu, 2013; Mydin et al., 2014; Othuman Mydin et al., 2014a, 2014b; Hardie et al., 2014; Xu et al., 2015; He and Park, 2017; Akashah et al., 2016; Liu et al., 2019; Akinciturk and Kilic, 2004; Du and Okazaki, 2016; Du et al., 2017; Yuan et al., 2018; Li et al., 2021; Salleh and Ahmad, 2009; Ibrahim et al., 2011b; Durak et al., 2011; Biao et al., 2012; Martokusumo et al., 2013), the level of fire safety of traditional or historic buildings, settlements and villages is critical, and the most common fire risks mentioned in the literature are: (1) insufficient water supply for firefighting operation, (2) difficult access for fire emergency services, (3) buildings in close proximity to each other without sufficient fire separation distance, (4) non-compliant means of escape, especially, for disabled people, (5) obsolete and unsafe electrical equipment under frequent overload, (6) large fire loads (e.g., combustible building materials, flammable decoration and furnishings), (7) low fire resistance rating due to the aging of structures, which are mainly made of timber, a combustible material whose ignition and fire propagation is especially favored when wood is in a dry condition and with cracks, (8) poor or non-existent fire safety management and, in many cases, lack of regular maintenance and upgrading of the fire safety equipment, if any, (9) lack of fire safety knowledge and awareness, and (10) low financial support to improve fire safety.

Finally, the development of maps depicting the magnitude of fire risk in historic city centers (Brimblecombe et al., 2020; Tozo Neto and Ferreira, 2020; Granda and Ferreira, 2021; Himoto and Nakamura, 2014) and traditional villages (Li and Deliberty, 2021) has recently become a quite common approach. Fire risk maps are very revealing in showing those areas that need to be prioritized for developing and establishing fire prevention and mitigation strategies. In this regard, most of the studies (Li and Deliberty, 2021; Brimblecombe et al., 2020; Tozo Neto and Ferreira, 2020; Granda and Ferreira, 2021) incorporated their data or results into GIS tools to obtain the corresponding maps. Thus, Granda and Ferreira (2021) applied a fire risk index developed by Ferreira et al. (2018), which considers fire ignition and spread, evacuation, and firefighting aspects, to assess the fire risk of the historic center of Quito, Ecuador. Results were combined with sociodemographic, vulnerability and accessibility, and crisis management capacity indicators to obtain the overall risk. Similarly, Tozo Neto and Ferreira (2020) assumed a fire risk index proposed by Ferreira et al. (2016) to evaluate the urban fire risk of the historic center of Guimarães, Portugal, before and after the application of risk mitigation strategies, and performed a cost-effectiveness analysis considering four different strategies. Brimblecombe et al. (2020), based on data from literature review and government reports, mapped the potential risk of different natural hazards, including fire, on heritage buildings in Tokyo, Japan. Along the same line, Himoto and Nakamura (2014) analyzed the post-earthquake fire risk of 2131 historic buildings in Kyoto City, Japan, based on an urban fire spread model and Monte Carlo simulation to assess their burn-down probability. Results revealed that up to 30% of the heritage buildings in the city center could suffer severe fire damage. Lastly, Li and Deliberty (2021) proposed the combined use of drones, participatory methods with local people, and GIS as an affordable approach to generate maps on fire risk and conservation status of historic buildings in indigenous communities with high cultural value in developing regions. The application of the methodology to two heritage villages in southwest China demonstrated its usefulness in improving the fire resilience of these communities, as well as the importance of the community contributions in the development of the maps.

It should be highlighted that, in addition to fire hazards, there are multiple risks that threaten the conservation of historic buildings and, therefore, the identification, assessment, and management of such risks is crucial to avoid heritage loss (Lucchi, 2020). Catastrophic events (e.g., earthquakes and floods), environmental risks (e.g., pollution and thermo-hygrometric variations), and physical, chemical, or biological degradation are examples of potential risks that can also affect historic buildings.

### 3.4. Fire protection and mitigation measures

Several studies have been published on the fire protection measures currently available to improve fire safety in historic buildings (Holschemacher and Quapp, 2019; Kincaid, 2018; Zahmatkesh and Memari, 2017). Zahmatkesh and Memari (2017) provided an overview of both conventional and innovative fire protection measures for existing buildings, including a description of the advantages and disadvantages of each of them. Likewise, Kincaid (2018) described different passive and active fire protection measures, and provided explanatory examples of historic buildings where these measures had already been applied. In particular, Holschemacher and Quapp (2019) focused on the strengthening of historic timber flooring systems with collaborating concrete slabs to enhance their fire resistance, among others. This solution allows the bottom side of the original timber flooring system to remain unaffected by the intervention. However, its use is hampered by the lack of regulations governing the fire design of timber-concrete composite systems (Holschemacher and Quapp, 2019). It is important to note that research on the effectiveness of fire protection measures has also been conducted. Specifically, Xiaomeng et al. (2010) theoretically and experimentally assessed the efficiency of portable water mist extinguishers in suppressing flammable liquid and wood crib fires in historic buildings. Results revealed that water mist features, namely the density and the speed and diameter of the water droplets, are determinant in the extinguishing efficiency.

Other authors have proposed the use of technical systems to assist in the management of fire emergencies in historic buildings (Guan et al., 2018; Doulgerakis et al., 2021), as well as to facilitate their preservation (Lercari et al., 2021). Guan et al. (2018) suggested the implementation of wireless networks in historic buildings to remotely provide real-time information on fire detection, as well as fire and smoke conditions and safe evacuation routes during a fire. Moreover, these networks can be of great help in performing and prioritizing fire safety management tasks in historic buildings. Doulgerakis et al. (2021) developed a platform for cultural heritage sites that incorporates procedures for semi-automatic digitalization of built heritage, simulation tools to analyze potential fire scenarios and crowd behavior, real-time fire detection and monitoring systems, and a decision support system for fire emergency management. Lastly, Lercari et al. (2021) presented a methodology for collecting and processing 3D geospatial data using remote sensing to be used for the visual assessment of damage to the built heritage after the occurrence of a natural disaster, such as a wildfire or an earthquake, as well as for the development of maintenance and monitoring plans.

The analysis of the fire protection status of heritage buildings has also been subject of numerous studies, especially in Asian countries (You et al., 2011; Dong et al., 2014; Kim et al., 2015; Zhang et al., 2015; Salleh and Mohtar, 2020; Fan, 2001). First, several studies carried out in Chinese heritage buildings (You et al., 2011; Dong et al., 2014; Zhang et al., 2015; Fan, 2001) came to similar conclusions, pointing out their high vulnerability to fire due to these being made of wood and containing high fire loads, the ease of fire spread between buildings, and the inadequacy or lack of fire protection measures. With the aim of improving the fire safety of heritage buildings, these studies proposed fire protection measures based on the identified fire hazards. Thus, Fan (2001) and Dong et al. (2014) suggested a combination of conventional fire protection systems, in conjunction with a reliable fire safety management. In particular, You et al. (2011) and Zhang et al. (2015) focused on the use of chemical flame retardants, namely sol-gel products, to improve the fire resistance of wooden elements of heritage buildings, without compromising their aesthetical appearance. Furthermore, sol-gel products can protect wood from the effects of weathering and biodegradation, among others (Hübert et al., 2017). Similarly, Salleh and Mohtar (2020) evaluated the existing active fire protection measures in four representative heritage buildings in Malaysia, which were generally found to had unreliable fire safety measures and poor fire safety management. Kim et al. (2015) evaluated the existing fire safety equipment at more than four hundred wooden heritage sites in Japan. In contrast to the previous studies, it was concluded that, in general, Japanese heritage sites have sufficient fire protection systems according to legal requirements, and that these are regularly maintained. However, Kim et al. (2015) strongly encouraged the creation of different cooperative organizations to improve fire safety, raise awareness, and help dealing with fire emergencies and rapid initial response. Lastly, Kupilík et al. (2013) focused on the assessment of fire safety in churches in Central Europe and proposed the use of electric fire alarm and smoke detection systems together with a well-designed ventilation to ensure fire safety.

One of the most challenging situations regarding the compliance with fire safety requirements of current regulations in historic buildings is when the use of the building is changed from the original one. Thus, Devi and Sharma (2019) focused on those Indian heritage buildings whose original use had been changed to become museums or libraries, and suggested innovative passive fire protection measures to improve the fire safety of these buildings as well as to protect their contents from fire without the need for irreversible interventions. These included fireproof curtains for compartmentalization and fire retardant coatings, among others. In the same vein, Aiello et al. (2002) compiled a series of fire safety design solutions adopted in a number of historic buildings adapted for university use with the ultimate goal of developing guidelines on the fire safety measures that could be implemented in such cases.

It should be noted that, although the majority of the previous studies assess the fire safety issues in wooden heritage buildings (You et al., 2011; Dong et al., 2014; Kim et al., 2015; Devi and Sharma, 2019; Salleh and Mohtar, 2020; Fan, 2001; Kupilík et al., 2013), similar studies have also been conducted in historic cast iron structures (Porter et al., 1998; Nieuwmeijer, 2001). Historically, cast iron structures gained a poor reputation since their fire performance was quite unknown and prejudices, often “exaggerated” (Porter et al., 1998), emerged among safety regulators. Currently, cast iron is no longer used as building material, so it lacks regulations or guidance documents, and research on it is practically non-existent. Within this context, Porter et al. (1998) and Nieuwmeijer (2001) promoted the preservation of historic cast iron structures and suggested a series of fire protection measures to upgrade their fire safety with the least possible impact on their architectural value.

Up to this point, studies discussing the fire safety measures that could be or have been adopted in historic buildings to upgrade their fire safety have been presented. However, there is also research regarding methods or models to select or prioritize those measures according to different aspects (Naziris et al., 2016a, 2016b; Kaplan, 2003). First, Kaplan (2003) presented a theoretical framework to weigh fire safety improvements considering their physical impact on historic buildings and, therefore, to assist in the decision-making process for selecting the set of fire safety measures to be adopted in a given historic building that entails minimal intervention while achieving an adequate level of fire safety. Nevertheless, fire protection design is usually conditioned by budget constraints, especially in historic buildings in which costly interventions are often required to preserve their architectural and cultural value. In line with this idea, Naziris et al. proposed the use of a generic selection and resource allocation (SRA) model developed by Lagaros et al. (2013) together with either a metaheuristic optimization-based approach (Naziris et al., 2016b) or an analytic hierarchy process (AHP) (Naziris et al., 2016a), the latter being a widely used technique in multi-criteria decision making (MCDM), for optimally upgrading the fire safety of a group of historic buildings to the highest possible level taking into account available budget and for establishing priorities. In this case, the proposed model was applied to a group of 20 monasteries in Mount Athos, Greece, and different feasible resource allocation solutions were obtained for different budget constraints and for different levels of fire safety.

On the other hand, the combination of fire protection measures with the development of a reliable fire safety management constitutes a key factor to achieve fire safety and to reduce fire risk and fire impacts in historic buildings, as reported in many studies (Akinciturk and Kilic, 2004; Li et al., 2021; Dong et al., 2014; Kincaid, 2018; Guan et al., 2018; Zahmatkesh and Memari, 2017; Salleh and Mohtar, 2020; Kaplan, 2003). Within this context, Marrion (2016) provided an overall framework to be used as guidance for the elaboration of an appropriate fire mitigation strategy for historic buildings that contemplates the adoption of prevention and mitigation measures, as well as the development of emergency response and disaster recovery procedures. Similarly, Kincaid (2019) provided guidance on how to approach the development of fire emergency planning in historic buildings considering proactive prevention, as well as planning for early and advanced stages of the fire and for the aftermath. Due to their complexity, Kincaid (2021) also recommended considering post-fire pre-reconstruction situations in the fire emergency planning for historic buildings to provide an organized and efficient response aimed at preventing further damage after the fire. Moreover, Kincaid (2012) sought to determine the extent to which the implementation of a robust fire safety management in historic buildings could replace physical fire safety measures to achieve the required level of fire safety. For this purpose, three country houses in Derbyshire, United Kingdom, were selected as case studies, and findings from literature review and interviews with fire safety experts revealed that the level of physical measures could be significantly reduced and, consequently, the degree of alteration of the historic buildings.

Finally, lessons learned from fires in historic buildings over time are highly relevant when addressing fire safety in existing historic buildings. Thus, Venegas et al. (2021) conducted a review of fires that occurred between 1990 and 2019 in significant heritage buildings worldwide, including the main causes that originated them. As a result, the principal issues that threaten the fire safety of heritage buildings were identified, and fire prevention and mitigation measures were recommended. Likewise, Bakas et al. (2020) discussed the particular features that make historic buildings vulnerable to fire, and provided guidance on how to protect them while respecting conservation principles. Vijay and Gadde (2021), based on the consequences of a serious fire that occurred in 2015 in the historic town of Harpers Ferry in the United States, examined the fire-related damages in historic buildings depending on the building material (i.e., timber, masonry and mortars, cast iron and steel). Lastly, Kincaid (2020) analyzed interventions that have been carried out on important historic buildings after being affected by fire and, based on literature review and interviews, concluded that the significance of the historic building, the level of fire damage, and the availability of funds and accurate documentation of the building prior to the fire are key factors in deciding whether reconstruction is a feasible option for the historic building.

### *3.5. Spread of both fire and smoke and evacuation*

#### *3.5.1. Spread of fire and smoke*

Within the studies dealing with the analysis of fire and smoke spread in historic buildings during a fire, three main typologies can be distinguished: those whose research is carried out through fire tests (Hasemi et al., 2002a; Peng et al., 2011; Zhou et al., 2021; Yang et al., 2022; Suzuki and Manzello, 2019), those using numerical simulations (Manuello Bertetto et al., 2021; Cao et al., 2021; Chen et al., 2015), and those combining both (Tung et al., 2020; Huai et al., 2021). Such studies are particularly helpful in developing more effective fire safety planning as well as safer evacuation planning for the occupants, among others.

First, Hasemi et al. (2002a) studied the spread of smoke in case of fire within the main tower of Himeji-jo Castle in Japan, which is a 30 m high timber building included in the UNESCO World Heritage List, through a 1/25 scale model. Results of the fire tests for different fire scenarios showed that certain architectural features of the tower contribute positively to fire safety and also provided information on which spaces would be engulfed in smoke or, on the contrary, would remain unaffected during the fire. In the same vein, Peng et al. (2011) conducted six full-scale fire tests in a historic wooden building in Lijiang, China, to analyze both fire and smoke spread within the building. The influence of fire source location, existence or not of ceiling and of water sprinkler system, and type of movable fire load on fire and smoke spread were also analyzed. Thus, except for the fire test in which sprinklers were installed, results showed a particularly high fire risk, since once ignition starts, fire can spread rapidly throughout the wooden building. Yang et al. (2022) recently performed a full-scale fire test of typical timber buildings in rural areas of Southwest China to analyze fire and smoke spread, maximum temperatures reached, and failure mechanisms. A total of four wooden compartments close to each other and arranged on two platforms simulating a traditional Chinese village on a mountainside were constructed. The fire test showed a rapid spread of smoke and fire from the compartment where ignition started to the rest of compartments, and total collapse of the compartments occurred in only about 30 min, which is a worrying situation in terms of fire safety in these remote and difficult to access traditional villages.

While previous studies (Hasemi et al., 2002a; Peng et al., 2011; Yang et al., 2022) deal with the experimental analysis of fire and smoke spread in entire historic buildings, others adopt a more specific experimental approach by focusing on a single element of historic buildings (Suzuki and Manzello, 2019) or by assessing the influence of several factors on such spread (Zhou et al., 2021). Suzuki and Manzello (2019) studied the ignition vulnerability of thatched roofs, which are frequently found in Japanese historic buildings, to firebrands showers. For this purpose, a series of fire tests on thatched roof assemblies were conducted using a reduced-scale continuous-feed firebrand generator at different wind speeds. Results showed that firebrands penetrated the assembly and accumulated on the surface and, once ignition was achieved, fire rapidly spread within the roof. Zhou et al. (2021), after concluding that natural weathering of wood over the years facilitates ignition (Zhou et al., 2019), experimentally assessed the influence of weathering, as well as both horizontal and vertical wood grain orientations, on upward fire spread in wood chips separated by 1–2 cm wide air gaps. Results showed that, compared to unweathered specimens, weathered ones exhibited lower mass loss rates, and longer burning durations, when flames spread parallel to wood grain orientation, and shorter in the opposite case.

On the other hand, Chen et al. (2015), concerned by the proximity of many Taiwanese historic buildings to urban settlements and their vulnerability to fire, researched the minimum safety distance between a historic building and surrounding buildings to reduce fire risk in historic buildings due to fire spread from other buildings. To this end, a historic temple in Taipei, Taiwan, was chosen as case study and fire spread was analyzed through a FDS model considering different distances between the temple and its surroundings and different fire source locations. The results were useful in providing guidance on fire protection and fire safety management. Cao et al. (2021) assessed the influence of the spatial arrangement of traditional settlements in Southwest China in the fire spread between historic timber buildings through numerical simulation based on fractal and seepage theory. Two traditional Chinese settlements were selected as case studies, and results showed a high fire propagation risk among their historic wooden buildings, which seriously threatens their preservation. Manuello Bertetto et al. (2021) recently developed a CFD model of the Notre-Dame cathedral in Paris to reproduce the spread of fire and smoke as well as the maximum temperatures reached in the devastating fire of April 2019. Then, based on the maximum temperatures reached by the masonry walls according to the numerical simulation, as well as on the potential increase in moisture content of the limestones due to water used in firefighting, an estimation of the residual compressive strength of the still existing load-bearing walls of the cathedral was provided.

Finally, Tung et al. (2020) combined both FDS models and full-scale room fire tests to analyze the fire growth and spread in terms of heat release rates and room temperatures in historic wooden buildings in Taiwan. The study also included in-situ fire load surveys for 102 rooms of 23 historic buildings in use to determine both fixed and movable fire loads to be considered in the room fire tests. As pointed out by the authors, the discrepancies that were obtained between the numerical and experimental results highlight the importance of assuming appropriate values for the model parameters to ensure the accuracy of the predictions without underestimating the fire risk, as well as to avoid proposing inadequate and inefficient fire safety design. Thus, Huai et al. (2021) analyzed the fire and smoke growth and spread of a historic wooden temple in Beijing, China, through a FDS model of the structure, and the values used in the numerical simulation of both pyrolysis kinetic and physical parameters of four species of historical wood from the temple were experimentally determined.

#### 3.5.2. Evacuation

This section includes studies on evacuation safety in fire situations in historic buildings. Basically, the studies collected can be divided into two thematic groups: those analyzing the evacuation safety in historic buildings (Lena et al., 2012; Caliendo et al., 2020) and, on the other hand, those proposing evacuation guidance systems (Bernardini et al., 2016; D'Orazio et al., 2016) or algorithms (Cao et al., 2020) to assist in guiding evacuation more efficiently and safely. These evacuation guidance support systems can be especially crucial in crowded buildings whose occupants are unfamiliar with their layout.

First, Lena et al. (2012) interviewed a group of 20 people with different types of disabilities in Sweden to assess how evacuation safety can be enhanced in historic buildings based on their own experiences. Among the problems reported by the participants, the most relevant were the level differences in evacuation routes for people with reduced mobility; orientation difficulties for people with visual impairments; and difficulty in detecting the sound of the evacuation alarm signal in the case of people with hearing disabilities. Participants also highlighted the lack of evacuation procedures in many historic buildings, which affects not only disabled people, but all users of the building. Therefore, the study revealed the need to improve accessibility as well as to develop fire evacuation plans in historic buildings. Caliendo et al. (2020) recently analyzed, for multiple fire scenarios, the evacuation conditions (smoke, gas temperatures …) of a one-exit multi-story historic building in Salerno, Italy, which is currently used as a museum, through CFD models. Then, an evacuation model and a pedestrian flow model were assumed to simulate the evacuation of the occupants from the historic building. Although results from the simulations showed the effectiveness of the existing fire safety plan and fire safety equipment in the building, Caliendo et al. (2020) strongly recommended the establishment of alert and guidance procedures for quicker and safer evacuation of the occupants. In this case, however, the influence that people with disabilities could have on the evacuation process was not considered.

On the other hand, as stated by (Bernardini et al., 2016; D'Orazio et al., 2016), current fire safety regulations establish massive and irreversible interventions to achieve fire safety in historic buildings. Evidently, this type of interventions compromise the conservation of the architectural and cultural value of heritage buildings. Within this context, Bernardini et al. (2016) and D'Orazio et al. (2016) proposed different evacuation guidance systems based on reversible interventions to help evacuate occupants in fire situations even in low visibility conditions and, thus, improve fire safety in historic Italian theatres. The intelligent evacuation guidance system proposed by Bernardini et al. (2016) suggests, by turning on electrically-illumined directional signals, the safest and least crowded evacuation routes considering smoke conditions and pedestrian flow, which are tracked throughout the evacuation process by sensors. On the other hand, D'Orazio et al. (2016) suggested a continuous wayfinding system placed on the floor and composed by photoluminescent materials. A historic theatre in Fabriano, Italy, was assumed as case study to assess the effectiveness of these systems through a validated fire evacuation simulator (Bernardini et al., 2016) and egress drills involving more than 100 people (D'Orazio et al., 2016). Results showed reductions in total evacuation time of up to 26% (Bernardini et al., 2016) and 25% (D'Orazio et al., 2016) compared to evacuation scenarios with the traditional punctual wayfinding system existing in the theatre. Further information on the above studies (Bernardini et al., 2016; D'Orazio et al., 2016) can be found in (Bernardini, 2017).

Finally, Cao et al. (2020) recently proposed an algorithm to determine, in real time, the optimal evacuation routes (i.e., those associated with the shortest evacuation times) for occupants in a fire emergency in heritage buildings taking into account the location of the occupants and the nearest exits. The algorithm also considers different evacuation models depending on whether there are staff guiding the evacuation or not. The application of the proposed algorithm to the Louvre Museum in Paris, France, using numerical simulations proved its effectiveness in guiding the evacuation of a dense crowd in a shorter time.

It should be noted that, although not part of the search results, the recent book by Gales et al. (2022) on fire emergency evacuation in heritage cultural centers is also a very valuable contribution to the topic of this section. Specifically, the book is based on a case study of a heritage cultural center in Canada for which three evacuation scenarios were considered and carried out. The book covers aspects such as the behavior of the occupants during the evacuations, architectural considerations for evacuation modelling, and evacuation strategies, among others.

### 3.6. Thermal and thermomechanical behavior of historic structures or materials

This section includes studies on the thermal and thermomechanical behavior of historic timber (Hasemi et al., 2002b; Garcia-Castillo et al., 2021; Chorlton and Gales, 2019; Zhou et al., 2019; Otto et al., 2017), masonry (Gomez-Heras et al., 2009; Vasanelli et al., 2021; Shao and Shao, 2018; Garrido et al., 2022), and cast iron (Maraveas et al., 2013, 2014, 2015, 2016a, 2016b, 2017) structures, which constitute the majority of the built heritage (Vijay and Gadde, 2021), as well as the performance of restoration mortars (Pachta et al., 2018, 2021; Demircan et al., 2021) and fire protection coatings for historic structures (Liblik et al., 2021; Chorlton and Gales, 2020; Kielė et al., 2020) at elevated temperatures. Evidently, most of the studies conducted experimental tests (Hasemi et al., 2002b; Garcia-Castillo et al., 2021; Vasanelli et al., 2021; Shao and Shao, 2018; Chorlton and Gales, 2019; Zhou et al., 2019; Otto et al., 2017; Garrido et al., 2022; Maraveas et al., 2015) or are based on the results of experimental tests reported in the literature (Maraveas et al., 2013, 2014, 2016a, 2016b, 2017).

First, the studies on the thermal and thermomechanical behavior of historic timber structures can be divided into two main groups: those analyzing the performance of the building material itself (Chorlton and Gales, 2019; Zhou et al., 2019; Otto et al., 2017) and those analyzing the performance of a particular traditional structural system (Hasemi et al., 2002b; Garcia-Castillo et al., 2021). Within the first group, Otto et al. (2017) investigated the performance of mass heritage timber under controlled fire exposure. For this purpose, fire tests on both heritage and contemporary (LVL and glulam) timber specimens were conducted. Comparison between charring depths and flame spread revealed that heritage timber had a similar fire resistance to contemporary timbers. Similarly, Chorlton and Gales (2019) compared the fire performance of two types of heritage timbers with two types of contemporary glulam. In this case, however, heritage timber did not perform as well as the glulam, as the former showed significantly higher charring rates. The different conclusions reached by these two studies highlight the lack of knowledge about the thermal behavior of heritage timbers, which jeopardizes the preservation of historic timber structures, so further research is required, as suggested by (Chorlton and Gales, 2019; Otto et al., 2017). In the same vein, Zhou et al. (2019) investigated the effect of natural weathering over the years on the reaction-to-fire performance of untreated and fire-retardant treated historic timber. Although the effect on chemically treated historic timber was less severe, experimental results indicated that the natural weathering process increases the total heat release and the peak heat release rate and reduces the ignition time. On the other hand, Hasemi et al. (2002b) evaluated the fire performance of typical wood-soil timber-framed walls of Japanese historic buildings through loaded fire tests. Results were optimistic compared to those established by the Japanese building code and proved that high fire resistance-ratings can be obtained for traditional timber construction. Likewise, Garcia-Castillo et al. (2021) numerically and experimentally assessed the fire resistance of historic timber jack arch flooring systems and concluded that, in numerous cases, historic buildings with these structural elements would not meet the requirements set by current codes and that the provisions of those codes for timber structures led to inaccurate and non-conservative predictions of the fire resistance of these traditional flooring systems.

Regarding the thermal and thermomechanical behavior of historic masonry structures, Gomez-Heras et al. (2009) conducted in 2009 a review of the available research on the effects of fire on stone-built heritage. Briefly, research in this field initially focused on macroscopic observations of cracking and color change, and lately on micro-scale processes, such as porosity changes, mineralogy, and micro-cracking, as well as the long-term effects of high temperatures on stone masonry. Among the main ideas reported by Gomez-Heras et al. (2009), it should be emphasized that fire can seriously affect the aesthetics of stone-built heritage, in addition to inducing a significant deterioration of the mechanical performance of building stones both in the short and long term. Moreover, water-based firefighting strategies may result in stone spalling due to water pressure and thermal shock. More recently, Shao and Shao (2018) evaluated the thermal and thermomechanical behavior of brick walls typical of Taiwanese historic buildings through FDS models and fire tests. Fire tests revealed that cracks and broken parts on the exposed surface of the brick walls significantly allowed the penetration and spread of heat and smoke. Therefore, even though bricks are not combustible, their deterioration can increase the vulnerability of heritage structures to fire. On the other hand, Vasanelli et al. (2021) experimentally studied the effects of high temperatures (up to 700 °C) on the performance of high porous calcareous stones typically found in masonry structural elements of historic buildings in Southern Italy. Experimental tests showed that temperature mainly affected the aesthetic characteristics of the stone due to color changes, and only limited microscopic fissures due to thermal expansion were detected. Furthermore, the use of non-destructive ultrasonic velocity propagation (UPV) testing for in situ diagnosis of hidden damage was validated. Similarly, Garrido et al. (2022) investigated the influence of high temperatures on the residual strength and hardness of a particular limestone extensively used in historic buildings in Eastern Spain. Although, the uniaxial compressive strength (UCS) test is the most frequently used to determine rock strength, it can only be performed in a laboratory and requires numerous samples, which makes its application to historic buildings unfeasible. Therefore, Garrido et al. (2022) proposed correlations to indirectly determine the UCS by means of the point load test (PLT) and non-destructive Leeb hardness tests (LHT). For this purpose, UCS, PLT and LHT tests were performed after cooling of the heated samples within the temperature range between 105 and 900 °C. Results demonstrated the suitability of the LHT test to indirectly estimate UCS using the proposed correlations.

Maraveas et al. researched in depth the thermal and thermomechanical behavior of historic cast iron structures. This research is of great relevance since both repealed and current building codes do not provide guidance for fire resistance analysis of these structures. First, Maraveas et al. (2013) gathered from literature the temperature-dependent thermal and mechanical properties of the materials constituting 19th century fireproof flooring systems, i.e. cast iron and associated insulation materials (early concrete or masonry). Note that the term fireproof refers to the use of non-combustible building materials. Given the scattering found in the data collected from the literature, Maraveas et al. (2014) proposed lower and upper boundary curves for both the thermal and mechanical properties of the materials and performed sensitivity analyses of the thermal and thermomechanical behavior of these typical flooring systems to assess the degree of uncertainty in the properties. Then, Maraveas et al. (2015) carried out a total of 135 mechanical tests, which included mainly tensile and compressive tests, on cast iron specimens at elevated and ambient (after cooling) temperatures. The results of such experimental tests were used to propose a thermal expansion coefficient and stress-strain-temperature relationships. It should be noted that, this research work on the thermal and mechanical properties at elevated temperatures of the materials of fireproof jack arched flooring systems (Maraveas et al., 2013, 2014, 2015) was the basis for subsequent studies by Maraveas et al., 2016a, 2016b, 2017 that analyze the fire performance of historic structures with cast iron structural elements. More specifically, Maraveas et al. (2016a) developed a simplified method to calculate the bending moment capacity of the cast iron beams of these traditional flooring systems subjected to the standard ISO 834 (ISO 834-1, 1999) fire exposure. Due to the wide dispersion of the temperature-dependent mechanical properties of cast iron (Maraveas et al., 2014), Maraveas et al. (2017) proposed material safety factors to establish different reliability levels in the fire safety design of jack arch cast iron beams and thereby assume an acceptable probability of structural failure in case of fire. The safety factors were derived from a probability distribution of the bending moment capacity, which was obtained through Monte-Carlo simulations assuming four characteristic cast iron cross-sections and random stress-strain-temperature relationships based on (Maraveas et al., 2016a, 2016b, 2017). Finally, Maraveas et al. (2016b) analyzed the fire resistance of cast iron columns common in many 19th century structures through ABAQUS simulation models.

On the other hand, the analysis of the high-temperature performance of mortars conceived for restoration purposes is very useful for selecting appropriate repair materials for historic structures that can contribute to the fulfillment of the fire safety requirements, as well as for assessing the post-fire residual strength capacity of historic masonry structures. In line with this objective, Pachta et al. (2018) assessed the structural behavior of five series of lime-based mortars exposed to elevated temperatures (up to 1000 °C). The mortars studied reproduced the features and components of historic mortars used in historic masonry, which in most cases used lime and lime-based binders (Pachta et al., 2018; Demircan et al., 2021), and showed a good behavior throughout the thermal tests, maintaining their physical and mechanical properties up to 800 °C. Due to the extensive use of brick waste in the manufacture of historic mortars, a similar recent study carried out by Pachta et al. (2021) evaluated the influence of high temperatures on the performance of lime-based mortar with brick dust and crushed brick, which replaced 40% of natural aggregates. Results from experimental tests at temperatures from 200 up to 1000 °C showed that brick residues improved the structural integrity and the residual strength of the mortar at high temperatures. Demircan et al. (2021) recently proposed a high-temperature resistant restoration mortar with polypropylene fibers in which the natural hydraulic lime normally used as binder was substituted by artificial pozzolans coming from industrial wastes (i.e., fly ash and blast furnace slag), thereby implying a significant contribution in terms of sustainability. Thus, experimental tests were carried out to determine the optimum proportion of the mortar components to achieve a high compressive strength as well as a satisfactory performance when exposed to temperatures of up to 600 °C, and it was concluded that the use of artificial pozzolans led to an increased resistance of the restoration mortar under elevated temperatures.

The combustible nature of wood has been, and continues to be, a major concern regarding the fire resistance of timber structures. One of the options to protect historic timber structures from the effects of fire is the use of encapsulations or fire protection coatings, which act as non-combustible barriers and, consequently, delay the ignition of the wood. Within this context, the fire performance of encapsulations or fire protection coatings that were typically used in historic timber structures

(Liblik et al., 2021; Chorlton and Gales, 2020), as well as of those recently proposed to protect existing timber structures (Kielė et al., 2020), has been the subject of several studies. First, clay and lime plasters have been widely used in historic timber structures as surface finish material. However, these plasters are not contemplated as fire protection coatings for timber under current regulations (CEN, 2004a), so no design guidelines are provided, and research on the topic is scarce. Thus, Liblik et al. (2021) experimentally and numerically evaluated the behavior, as well as the thermal properties at elevated temperatures, of these plasters under the standard ISO 834 (ISO 834-1, 1999) fire exposure. Although further research is needed, a valuable contribution of this study is the tentative proposal of design parameters to perform fire resistance assessment of historic timber structures initially protected against fire with clay or lime plasters following the methodology of EN 1995-1-2 (CEN, 2004a). In the same vein, Chorlton and Gales (2020) recently reviewed the evolution over time of encapsulations to improve the fire safety of timber elements, and experimentally assessed the fire performance of some heritage and contemporary encapsulations, including plasters, metal plates, lime-based paints, and gypsum boards. Results showed that none of the historic encapsulations successfully protected the timber and, therefore, their contribution to fire safety should be neglected, even if they are kept due to heritage preservation reasons. Lastly, Kielė et al. (2020) investigated the fire performance of alkali-activated slag plaster reinforced with polypropylene fibers for use as fire protection coating in historic wooden buildings. To this end, three experimental tests under the standard ISO 834 (ISO 834-1, 1999) fire exposure were conducted, concluding that the coating significantly delayed the onset of wood charring and that the polypropylene fibers showed great benefits in maintaining the integrity of the plaster throughout the fire tests, as well as in improving its thermal properties.

### 3.7. *Fire safety engineering design*

Performance-based approaches, also known as fire safety engineering approaches, can enable the preservation of historic buildings when prescriptive approaches are overly demanding or not applicable. Performance-based approaches also allow singular fire safety designs to be proposed that respect the architectural and cultural value of historic buildings, provided that the required level of fire safety is achieved.

Within this context, multiple studies collected from the literature describe how performance-based approaches have been used in the fire safety design of existing structures (Pau et al., 2019; De Medici et al., 2019; Petrini et al., 2022; Miano et al., 2020; Węgrzyński et al., 2020; Wouters and Mollaert, 2003; Tsui and Chow, 2007; Bukowski and Nuzzolese, 2009; Frosini et al., 2016; Takács and Szikra, 2017). First, in the absence of applicable regulations, Wouters and Mollaert (2003) showed how the fire resistance of the cast iron columns of three 19th century fireproof buildings under renovation subjected to a natural fire exposure established by EN 1991-1-2 (CEN, 2002), namely a two-zones model, could be evaluated. For this purpose, the software OZone (Cadorin and Franssen, 2003; Cadorin et al., 2003) was used to define the corresponding natural fire curves, as well as to predict the temperature of the columns throughout each fire exposure. Note that Maraveas et al., 2016a, 2016b, 2017 also assumed performance-based approaches to analyze the fire behavior of historic cast iron structures, specifically the beams found in jack arched flooring systems and columns. Takács and Szikra (2017) described the performance-based fire safety design developed for the refurbishment of the Eiffel Hall, which is the largest and one of the most important listed historic buildings in Hungary. In this case, a CFD model was used to ensure effective cooperation between the proposed active fire protection systems, as well as safe evacuation conditions within the required time. Also based on CFD simulations, Węgrzyński et al. (2020) evaluated the performance of a smart smoke control (SSC) solution, which takes advantage of existing ducts, in removing the smoke generated in a fire in a confined underground cellar area with limited ventilation of a historic building converted into a restaurant. Results showed that the SCC system was able to remove 50% more smoke than the traditional smoke venting system, which turned out to be essential to guarantee safe evacuation conditions during the prescribed period. Similarly, D'Orazio et al. (2016) and Bukowski and Nuzzolese (2009) resorted to the use of CFD and finite element models, respectively, to propose the fire safety design of two historic theatres under restoration in Italy. In the same line, Miano et al. (2020) assessed the fire resistance of a historic palace in Caggiano, Italy, assuming both prescriptive and performance-based approaches. Specifically, the most restrictive structural element was a reinforced concrete flooring system whose fire resistance was determined based on tabulated data from EN 1992-1-2 (CEN, 2004b) and, on the other hand, an advanced finite element model of the structure under the standard ISO 834 (ISO 834-1, 1999) fire exposure and a two-zones model (CEN, 2002). Results showed that the flooring system was not code-compliant only when considering the prescriptive approach. Likewise, Tsui and Chow (2007) applied prescriptive and performance-based approaches to the fire safety design of a heritage building converted into a hotel in Hong Kong. While the prescriptive approach led to fire safety design solutions with a large impact on the building, the performance-based approach proved that the original building meets the provisions of the regulations without requiring any intervention.

Notwithstanding, the adoption of performance-based approaches is complex and time-consuming. In this way, New Zealand building code proposes several design scenarios to facilitate and delimit the fire safety engineering design process. Even though, the methodology sets prescriptive requirements, flexibility to ensure heritage preservation is allowed, which was a key factor in the fire safety design developed by Pau et al. (2019) for the refurbishment of a heritage building in New Zealand. Also to promote the use of fire safety engineering approaches, Frosini et al. (2016) defined a procedure to achieve interoperability between Building Information Modelling (BIM) software and fire safety software to enable the exchange of information digitally.

In general, as it is apparent from the above studies, performance-based approaches to assess the fire safety of heritage buildings or the effectiveness of proposed fire protection measures have been carried out assuming deterministic approaches. However, the use of probabilistic approaches is essential to ensure reliability of structural fire safety designs. While probabilistic approaches are fully established in fields such as seismic engineering (Flenga and Favvata, 2021; Xu et al., 2018) and major research progresses have been achieved in the field of structural fire engineering for current structural systems (Gernay et al., 2019; Molkens et al., 2017), their application to historic buildings has barely been addressed. Particularly, Petrini et al. (2022) carried out the probabilistic fire risk assessment of a wooden roof of an existing heritage building in Italy, based on the event-tree analysis technique for which different potential fire scenarios were considered. For this purpose, numerical simulations were performed to determine the structural response of the roof to each fire scenario and, as a result, fire risk curves associated with a given return period were provided. Nevertheless, as stated by Petrini et al. (2022), the lack of guidance on the application of probabilistic approaches to performance-based fire safety assessment of heritage buildings, as well as the lack of applicable robust probabilistic models, question the reliability of such assessments and, therefore, further research efforts in this field are necessary. Note that the study by Maraveas et al. (2017) proposing material safety factors for cast iron is also a significant contribution within this field.

On the other hand, as discussed in previous sections, current codes do not provide methods applicable to the evaluation of the fire resistance of existing historic structures. Since this assessment is required when renovating or changing the use of existing buildings, the lack of verification methods constitutes a major problem for preserving historic buildings, especially in those cases whose building materials or construction techniques are no longer in use. Thus, this issue has been reflected in numerous studies in which procedures based on the verification methods established by current Eurocodes have been proposed to be applicable to historic structures (Garcia-Castillo et al., 2021; Wouters and Mollaert, 2002; Król, 2016; Szumigała and Polus, 2017). In particular, Wouters and Mollaert (2002) described how the methods established by EN 1993-1-2 (CEN, 2005) to verify the fire resistance of steel structures could be applied for the same purpose to 19th century cast iron framed structures. This is supported by the study by Maraveas et al. (2016b), which concluded, based on the results of the ABAQUS simulation models, that the assumption of EN 1993-1-2 (CEN, 2005) methodology can provide safe and reasonably accurate estimates of the strength and fire resistance of cast iron columns. In the same vein, Król (2016) and Szumigała and Polus (2017) illustrated through case studies how to evaluate the fire resistance of traditional flooring systems with steel joists hidden within the slab thickness, which were commonly used in Europe at the end of the 19th century, according to EN 1993-1-2 (CEN, 2005). From experimental test results, Garcia-Castillo et al. (2021) proposed a methodology based on the reduced cross-section method, a simplified mechanical method of the EN 1995-1-2 (CEN, 2004a), to verify the fire resistance of historic timber jack arch flooring systems. Basically, the methodology consists of assuming the 135 and 300 °C isotherms as the positions of the zero-strength layer and the charring depth, respectively. Lastly, Iringová and Idunk (2017) directly applied the methods established by EN 1995-1-2 (CEN, 2004a) to assess the fire resistance of a timber roof truss of a historic building under renovation in Slovakia.

Finally, research aimed at evaluating the potential severity of fires in historic buildings is highly relevant, since findings can be used as input in subsequent performance-based approaches to the fire safety design of these buildings. In this context, several studies have been conducted to determine the density values for both fixed and movable fire loads (Tung et al., 2020; Huai et al., 2021; Claret and Andrade, 2007; Li et al., 2020) or only for movable fire loads (Su et al., 2020), as well as the maximum heat release rate (Chang et al., 2021). Note that fire loads are classified as fixed (e.g., structural elements) or movable (e.g., furniture) depending on whether their presence is permanent or variable over time. Thus, Claret and Andrade (2007) surveyed 43 historic buildings in Ouro Preto, Brazil, and an overall average fire load density of 2989 MJ/m$^2$ was obtained. Moreover, the average values according to the room use were compared with those prescribed by Brazilian standards and the former were found to be up to 10 times higher. Likewise, Li et al. (2020) evaluated 83 historic wooden buildings in Beijing, China, and an average fire load density of 2847.7 MJ/m$^2$ was determined, in which the average contribution of the fixed fire load was more than 90%. It should be noted that, based on statistical analysis of the results, Li et al. (2020) also proposed a matrix to estimate the total fire load density of historic buildings as a function of the floor area and building use. Huai et al. (2021) performed in-situ fire load surveys in an accredited historic wooden temple in Beijing, China. As a result, a fixed fire load density of 4383.88 MJ/m$^2$ and a movable fire load density of 970.21 MJ/m$^2$ were obtained. Tung et al. (2020) investigated 102 rooms of 23 historic wooden buildings in Taiwan to define representative fire load densities as a function of the room use to be considered in subsequent room fire tests. In this case, the maximum average fire load density was associated with storage rooms, with a value of 417.8 MJ/m$^2$. Unlike the aforementioned studies, Su et al. (2020) evaluated only the movable fire load densities of 102 rooms in 21 Japanese-style historic wooden buildings in Taiwan, based on in-situ fire load surveys and cone calorimeter tests. The highest average value was obtained for memorial buildings (296.25 MJ/m$^2$) and, if considering the rooms independently, for storage rooms (431.38 MJ/m$^2$). In addition, strong correlations between movable fire load densities, floor area and room use were found. Lastly, Chang et al. (2021) determined through FDS the maximum heat release rate that could govern a fire in a specific historic church with a large presence of wood in Taiwan, and proposed the corresponding fire protection measures.

## 4. Discussion

### 4.1. Discussion of the results

Historic buildings were erected long ago, when modern building codes had not yet been enacted. For this reason, historic buildings often do not meet the requirements of current regulations, such as fire safety. Early fire safety regulations established prescriptive approaches to propose fire safety designs that theoretically provided an adequate level of fire safety in buildings. Prescriptive approaches are very rigid in their application and, what is more, the performance of their fire safety designs is never assessed. Thus, as reported in the literature, the architectural and historic value of many historic buildings has been seriously affected by massive interventions, which can be totally unnecessary or avoidable, to fulfill fire safety requirements (Torero, 2019a, 2019b).

Over the years, fire safety regulations have evolved to include performance-based approaches that allow flexibility in fire safety designs as long as performance requirements are satisfied. Many authors concur that performance-based approaches are in most cases the only way to address fire safety in historic buildings while preserving the built heritage (Marchant, 1989; Torero, 2019a, 2019b; Quapp and Holschemacher, 2020; Malhotra and Papaioannou, 1991; Watts, 2001; Phillips, 2010; Morrison and Hamre, 2018; Yuan et al., 2018; Durak et al., 2011; Biao et al., 2012; De Medici et al., 2019; Miano et al., 2020; Tsui and Chow, 2007; Bukowski and Nuzzolese, 2009). However, historic buildings still face numerous challenges with regard to fire safety regulations. Current fire codes focus on life safety, rather than protecting the buildings and its contents. The latter may be acceptable for contemporary buildings, but not for historic ones, whose valuable contents and fabric are irreplaceable. In the same vein, the methods established by current codes are generally conceived for new construction and, therefore, are not always suitable for historic or existing buildings. Lastly, the lack of specific guidelines to deal with fire safety in historic buildings is an issue that affects many countries (Morrison and Hamre, 2018; Martokusumo et al., 2013; Devi and Sharma, 2019; Salleh and Mohtar, 2020).

On the other hand, the literature reflects a great concern about the vulnerability of historic buildings to fire. In particular, several studies have proposed different indexes to quantify their fire risk and many others have qualitatively, quantitatively or probabilistically assessed such risk in existing built heritage. Overall, these studies report a critical level of fire safety in historic buildings, villages and city centers. In contrast to contemporary buildings, the fire safety of historic buildings is frequently threatened by issues such as the presence of high fire loads, low fire resistance ratings due to aging buildings, or insufficient fire separation distances between buildings. Besides the foregoing, many historic buildings face problems such as the lack of heritage preservation and fire safety awareness among the stakeholders or the lack of financial support, resulting in limited fire safety measures and a poor fire safety management.

Predictably, in view of the alarming situation, there are also many studies that focus on the fire protection and mitigation measures that can be applied to historic buildings to improve their fire safety. Basically, the suggested measures consist of the implementation of active and passive fire protection systems, together with reliable fire safety management and fire emergency planning. As stated by several authors, the adoption of proper management and emergency planning in historic buildings can be key to prevent many fire incidents or reduce their impact (Li et al., 2021; Marrion, 2016; Kincaid, 2019, 2021; Venegas et al., 2021), as well as to significantly decrease the level of physical measures needed to achieve the required level of fire safety (Kincaid, 2012). This aspect is of great relevance in historic buildings, as physical interventions will always affect to some extent the aesthetics of the building. In any case, as can be deduced from the literature, fire safety of historic buildings should be carefully addressed on a case-by-case basis and assuming performance-based approaches due to the uniqueness of these buildings. Along the same line, the literature also includes studies that apply methodologies to prioritize the implementation of fire safety measures in some historic buildings over others based on their fire risk (e.g., fire risk maps (Li and Deliberty, 2021; Brimblecombe et al., 2020; Tozo Neto and Ferreira, 2020; Granda and Ferreira, 2021; Himoto and Nakamura, 2014)), as well as to select certain measures over others considering factors such as their physical impact on the historic building (Kaplan, 2003) or economic constraints (Naziris et al., 2016a, 2016b).

The spread of fire and smoke during a fire in historic buildings has been analyzed both numerically and experimentally. These analyses are of great help to address fire safety designs more effectively. The spread of fire and smoke is a complex phenomenon that depends on numerous factors. However, the studies gathered from the literature generally agree that, once ignition starts, fire spreads easily throughout the historic building, especially if it is made of wood. Wooden elements can represent a considerable part of the fire load and natural weathering of wood has been found to facilitate ignition (Zhou et al., 2019). Moreover, since historic buildings are often located in historic city centers, whose streets are typically narrow, the fire propagation risk between buildings is usually high.

Regarding evacuation in case of a fire emergency, many historic buildings lack fire evacuation procedures or, in many cases, those implemented are inadequate or insufficient. This compromises life safety, especially when the occupants are unfamiliar with the building. On the other hand, historic buildings rarely meet the evacuation requirements established by current regulations. As a result, massive and irreversible interventions have been carried out in numerous historic buildings to bring them into compliance. In light of this problem, several studies collected from the literature propose systems and algorithms to guide the evacuation that require minimal intervention. In addition, performance-based approaches can be adopted to demonstrate that safe evacuations can be guaranteed without resorting to interventions that severely damage the architectural and cultural value of built heritage.

Understanding the thermal and thermomechanical behavior of historic building materials is essential for assessing the fire resistance of historic buildings and, consequently, ensure heritage preservation. Thus, multiple studies collected from the literature focus on the experimental analysis of the fire performance of historic masonry, cast iron and timber. First, several studies have concluded that historic masonry structures retain a significant fraction of their strength up to 700 °C (Vasanelli et al., 2021; Garrido et al., 2022). In addition, restoration mortars to help meet the fire safety requirements and improve the mechanical capacity of these structures, both at ambient and elevated temperatures, have been proposed (Pachta et al., 2018, 2021; Demircan et al., 2021). On the other hand, although the fire behavior of historic cast iron structures has not been extensively researched experimentally, various studies agree that it is quite similar to that of current steel structures (Maraveas et al., 2016b; Wouters and Mollaert, 2002). Lastly, based on the literature, the performance of historic timber under fire is not yet well understood (Chorlton and Gales, 2019; Otto et al., 2017) and, therefore, further research is needed. Moreover, the provisions of current codes for the structural fire design of timber structures do not seem to be applicable to historic timber structures (Hasemi et al., 2002b; Garcia-Castillo et al., 2021). It is true that historic timber members can be protected from fire by encapsulations or fire protection coatings. However, these affect the architectural value of the historic structure, which is not desirable. In any case, the contribution to fire safety of existing historic encapsulations should be neglected, as they do not always provide adequate or sufficient fire protection (Chorlton and Gales, 2020).

Finally, existing buildings must fulfill the requirements of current regulations whenever they are refurbished or their use is changed. As discussed above, prescriptive provisions are sometimes too demanding for historic buildings, which were designed when modern codes did not exist. In addition, such provisions are not always applicable to historic buildings due to their uniqueness. Therefore, numerous studies collected from the literature show how performance-based approaches have been applied to meet the fire safety requirements in historic buildings while preserving their architectural and cultural value. Furthermore, performance-based approaches also enable to assess the effectiveness of fire safety designs and thus avoid providing more fire protection measures than necessary, which is crucial for heritage conservation. Despite the foregoing, these approaches are complex and time-consuming, so their adoption remains limited (De Medici et al., 2019).

### 4.2. Statistical analysis

A simple (symmetric) correspondence analysis (Beh and Lombardo, 2014) to identify the most researched fields, as well as knowledge gaps, was conducted using the SPSS software (SPSS Inc, 2007). Basically, a simple correspondence analysis is a multivariate statistical technique that reveals the relative relationships between and within two sets of categorical data. In this case, the two different categorical variables considered were the research fields into which the studies collected from the literature were classified and the material on which each study focuses. Thus, a total of five material categories were established: timber (M1); timber and masonry walls (M2); protection or repair materials for historic structures (M3); cast iron or steel (M4); and studies not associated with any particular material (M5). Recall that the research field categories were as follows: fire safety regulations (R1); fire risk assessment (R2); fire protection and mitigation measures (R3); spread of both fire and smoke and evacuation (R4); thermal and thermomechanical

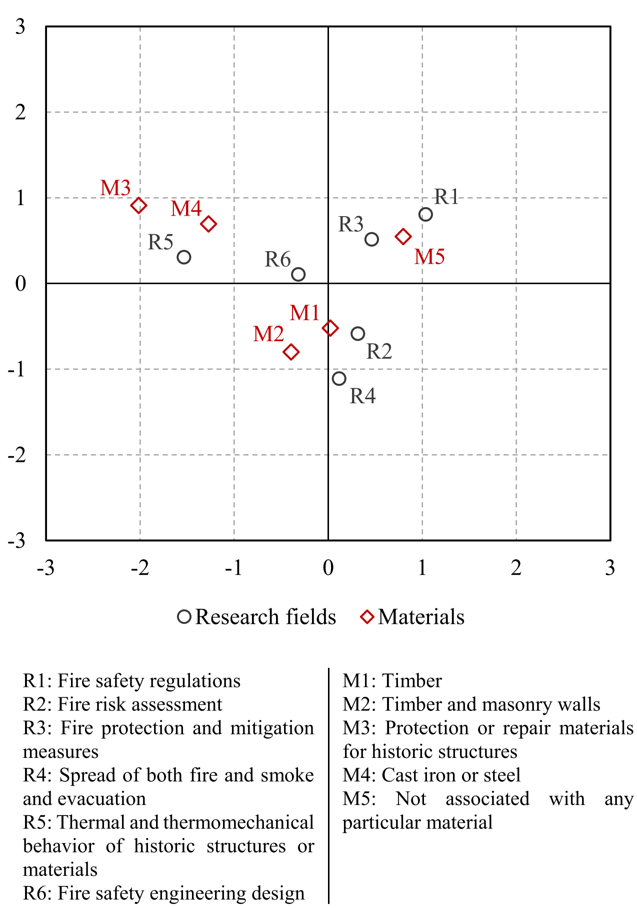


**Fig. 5.** Simple correspondence analysis of the research fields and materials investigated in the studies.

behavior of historic structures or materials (R5); and fire safety engineering design (R6). Prior to performing the simple correspondence analysis, a contingency table summarizing the frequency distribution of the simultaneous observations of the two categorical variables was constructed to be used as input for the analysis. Then, chi-square distances were assumed in the statistical analysis through the SPSS software to measure the relationships between the categories of the variables.

Fig. 5 shows the results of the simple correspondence analysis. Note that the closer the points representing the different categories are to each other, the stronger the relatedness between them, and vice versa. From the results, three main clusters of points can be distinguished: R1-R3-M5; R5-M3-M4; and R2-R4-M1-M2. First, it seems consistent that the research field categories corresponding to fire safety regulations and fire protection and mitigation measures are close to that of the M5 material category, since studies belonging to R1 and R3 generally focus on achieving an adequate level of fire safety in historic buildings without addressing any specific material. On the other hand, the proximity between the points R5, M3 and M4 indicates that many of the studies related to cast iron or steel structural elements or to protection or repair materials for historic structures analyze the thermal and thermo-mechanical performance of these materials. However, a small number of studies consider these materials, so it cannot be concluded that research in this field is consolidated. In contrast, as suggested by the group of points R2-R4-M1-M2, studies associated with timber or timber-masonry structures tend to focus on the fire risk assessment of historic buildings, as well as on the analysis of fire and smoke spread and evacuation in case of fire emergency in such buildings. The latter reflects concerns about the vulnerability of historic buildings with timber structural elements to fire. Even so, research on the thermal and thermomechanical behavior of historic timber is still relatively scarce. In fact, of the 125 studies gathered from the literature, 64 are related to timber or timber-masonry structures and only 5 of them investigate the thermal and thermo-mechanical performance of the material. While the thermomechanical behavior of cast iron or steel used in historic structures appears to be quite similar to that of contemporary structural steels (Maraveas et al., 2016b; Wouters and Mollaert, 2003), the fire performance of historic timbers remains unclear (Chorlton and Gales, 2019; Otto et al., 2017). Note that the large number of historic buildings with timber structural elements that still persist could explain the numerous studies that focus on them. Furthermore, unlike other building materials, timber is a combustible material, which makes it more vulnerable to fire, and its natural weathering favors ignition (Huai et al., 2021; Zhou et al., 2019). Lastly, it is important to note that the fire safety engineering design research field category is not particularly close to any other category, as it can be associated with any of them.

To sum up, there seems to be a general lack of knowledge regarding the thermal and thermomechanical behavior of historic materials and structures. As noted in the literature, achieving an acceptable level of fire safety while ensuring heritage preservation often requires fire safety engineering designs. To this end, thermal and thermomechanical characterization of historic materials is essential to obtain reliable predictions of the performance of historic structures during a potential fire.

### 4.3. Future research areas

This review has identified several areas where additional research is needed. First, while a major research effort has been devoted to the study of the thermal and thermomechanical behavior of contemporary building materials at elevated temperatures, research on historic building materials is scarce and, as a result, current fire codes do not provide specific provisions for historic building materials. However, understanding their thermal and thermomechanical behavior is essential to ensure the reliability of the simulations used to verify the fire resistance of historic buildings and their evacuation conditions in case of fire, among others. Therefore, further research on the fire performance of historic building materials is required. In this regard, given the large number of historic wooden buildings with high vulnerability to fire as well as the disparity in the results of studies gathered from the literature, it seems clear that timber deserves special attention.

On the other hand, probabilistic performance-based approaches can be of great help to take more informed decisions regarding the compliance of fire safety requirements. However, there is a lack of general guidance and demonstrative case studies to illustrate how to apply these approaches to historic buildings. To bridge this gap, it is first necessary to develop robust probabilistic models of the uncertain parameters involved in the fire analyses of historic buildings. These parameters include, among others, temperature-dependent thermal and mechanical properties of historic building materials for different fire exposures (e.g., temperature-dependent timber thermal properties included in EN 1995-1-2 (CEN, 2004a) are valid only for the standard ISO 834 (ISO 834-1, 1999) fire exposure), as well as the permanent, live and fire loads typical of historic buildings. Fire loads are especially important, because this review shows that they have an important variability and can be significantly higher than those proposed by current codes for new buildings. Thus, the fire risk of historic buildings can be underestimated. Therefore, research is required to provide values of fire loads depending on the use of the historic building. Note that probabilistic models to characterize the reduction of compressive and tensile strengths of timber as a function of temperature have been recently proposed by Garcia-Castillo et al. (n.d.).

Finally, fire codes should implement research advances and establish specific guidelines and methods for historic structures and buildings facilitating the adoption of performance-based approaches through simplified methods.

## 5. Conclusions

This study presents a literature review on the progress of fire research in heritage and historic buildings. Specifically, the present paper examines a total of 125 studies published between 1985 and 2022. These studies were classified into 6 different research fields: fire safety regulations (11%); fire risk assessment (23%); fire protection and mitigation measures (23%); spread of both fire and smoke and evacuation (12%); thermal and thermomechanical behavior of historic structures or materials (17%); and fire safety engineering design (14%).

Based on the search results, the topic covered by the present literature review has gained considerable attention in recent years. The establishment in 2015 of the SDGs might have lately promoted research in this field since the topic of the literature review is closely related to the 11th and 12th SDGs. The ultimate goal of research in this field is to protect built heritage from fire hazards, which contributes to achieving target 11.4 of the 11th SDG. On the other hand, such research can prevent the demolition of many historic buildings for not being able to meet fire safety requirements, thereby contributing to a more sustainable construction. Thus, in relation to the 12th SDG, rehabilitating and reusing historic buildings helps to meet targets 12.2 and 12.5 on the sustainable and efficient use of natural resources and on the reduction of waste generation, respectively.

Despite advances in research, the literature reflects that the situation of historic buildings regarding fire safety remains alarming. First, the fact that historic buildings were erected many years ago implies that they were designed without regard to the stringent fire safety requirements of current codes. For this reason, historic buildings are often very vulnerable to fire and making them meet such requirements constitutes a major challenge. On the other hand, current fire codes do not generally provide specific provisions for historic buildings, which threatens their preservation when fire safety cannot be verified. In addition, these codes focus on life safety rather than on the building and its contents. Therefore, applying their prescriptive approaches to meet fire safety requirements in historic buildings often entails adopting measures that seriously affect their architectural value. Consequently, performance-based approaches are frequently the only way to achieve compliance with fire safety requirements while preserving heritage. However, to date, the application of these approaches also has limitations and further research is needed to overcome them, as suggested in the previous section. Furthermore, it is essential that fire codes establish specific guidelines and methods for historic structures and buildings.

In summary, this paper provides a state of the art of research on fire in historic buildings. In addition, based on the literature review and a statistical analysis conducted to identify knowledge gaps, future lines of research aimed at achieving fire safety in historic buildings have been proposed. Thus, it is expected that this paper will help to promote the conservation of heritage and historic buildings, as well as to decrease the environmental impact of construction.

## Declaration of competing interest

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

## Data availability

No data was used for the research described in the article.

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