Heritage on Fire – Complexities, Potential Solutions and Current Regulations: An Exploratory Study

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Abstract
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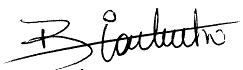

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Resumo

Este estudo tem como objetivo investigar, compreender e explorar questões relacionadas com a adequação das soluções existentes para a proteção contra incêndio em edifícios históricos e sua eficácia em evitar catástrofes. Sendo assim, artigos recentes, estudos de caso, documentos estatutários e diretrizes são revisados.

Uma breve explicação das razões pelas quais esse estudo foi realizado e sua relevância é fornecida, seguida da apresentação de potenciais soluções para segurança contra incêndio em edifícios históricos que não conflitem com os principais princípios de conservação.

A inadequação da aplicação das atuais normas de incêndio em edifícios antigos também é discutida em contraste com uma abordagem individial baseada em risco, a qual foi provada ser mais apropriada para esse tipo de edificação.

Além disso, na tentativa de propor contribuições de pesquisa mais consistentes, uma análise detalhada dessa problemática no contexto da vida real foi desenvolvida por meio de um questionário online para coleta de dados de pesquisa primários, seguido de uma aplicação prática. O questionário teve como objetivo analisar questões específicas relativas à aplicação de métodos de segurança contra incêndio em edifícios históricos em diversos países, dentro dos limites das legislações nacionais de cada país, pela ótica de profissionais experientes.

Já o estudo de caso, ou aplicação prática, foi projetado para explorar, comparar e demonstrar a pertinência de diferentes normativas e abordagens quando aplicadas em um mesmo edifício histórico.

Concluiu-se, então, que para viabilizar soluções adequadas que respeitem a singularidade do edifício é de suma importância avaliar criticamente as condições e riscos de cada edifício individualmente. Além disso, sempre que possível, engenheiros de incêndio, governos e órgãos conservadores devem combinar responsabilidades e unir esforços para envolver as comunidades, aumentar as contribuições de pesquisa, reunir recursos financeiros e desenvolver estratégias de gestão eficientes para garantir que soluções eficazes sejam fornecidas para edifícios de interesse especial.

Table of contents

List of Abbreviations

ANARP	As Near ad Reasonably Practicable
ASET	Available Safe Escape Time
BE	Fire Blocks Exit
BSI	British Standard Institution
CF	Challenging Fire
CS	Fire Starts in a Concealed Space
C/VM2	Verification Method – framework for fire safety design
FO	Firefighting Operations
FRA	Fire Risk Assessment
FRI	Fire Risk Indexing
FSC	Fire Safety Certificate
HS	Horizontal Fire Spread
IMFSE	International Master of Science in Fire Safety Engineering
IS	Rapid Fire Spread Involving Internal Surface Linings
RC	Robustness Check
RSET	Required Safe Escape Time
SF	Smoldering Fire
TGD-B	Technical Guidance Document B
UT	Fire in Normally Unoccupied Room Threatening Occupants of Other Rooms
VS	External Vertical Fire Spread

List of Figures

List of Tables

1. Introduction & Objectives

In this introductory chapter, an overview of the background is briefly presented to provide the basis of what is going to be explored and discussed in this research paper. Further, a detailed description and clarification about the objectives and limitations are given.

1.1 Background

It is known that the development and enforcement of appropriate fire protection standards are often triggered by unexpected large-scale fire incidents. After several large fire incidents that have occurred in heritage assets, it has become imperative to increase the levels of the building's fire protection, by employing research and effective incorporation of adequate solutions, in order to avoid future catastrophes.

Recent fire incidents with an irreversible loss to human cultural heritage and history include but are not limited to, the Brazilian National Museum in September 2018 (Brazil), Notre Dame (France) in April 2019, and Shuri Castle in Okinawa (Japan), in October 2019, among many others. The exact number of such events is unknown due to lack of statistical data. This lack of data hinders the factual proportion of loss of historic buildings due to fire. The situation worsens when combined with people's general lack of knowledge or interest regarding innovative solutions and available measures to avoid the destructive effects of fire and smoke (K. Papaioannou, 2003).

When it comes to historic buildings protected by a statutory conservation body, design for fire safety becomes even more challenging since they are not only under inflexible and restrictive fire safety prescriptive requirements (Baskas et al., 2020) but also subjected to several extra minimum requirements based on conservation principles. Because these ground rules for conservation of the heritage aim to safeguard the building's uniqueness and cultural significance, they shall be included in all steps of the design process in combination with the fire-engineering principles (Bakas et al., 2020; Quapp & Holschemacher, 2020). Thus, posing additional constraints on the project.

These conservation principles are translated basically into the provision of solutions that are minimally invasive, aesthetically sympathetic, and reversible (Australia ICOMOS, 2013). While the basic fire safety engineering principles include preventing fire initiation, life safety, property and environmental protection, and limitation of damage caused by fire and smoke (BS 7974, 2019). However, given the fact that many features and aspects of historic buildings can pose a challenge for fire safety by being a hazard themselves (Torero, 2019), it becomes extremely difficult and complex to comply with the prescriptive regulations while respecting the conservation principles, since some protective measures can be inadmissible (i.e., sprinklers, compartmentation). Some examples of the above-mentioned intrinsic hazards that can represent a fire risk in historic buildings and might not be removed due to their irreplaceable value are furniture, wall materials, objects, or even the load-bearing structure itself.

Therefore, due to the complex nature of this problem, a performance-based or engineering approach becomes utterly necessary. This is because since every cultural heritage is unique (different building, occupant, and fire characteristics), general solutions are most likely either excessive, costly or extremely intrusive. Hence, without the establishment of clear design objectives that define the general level of fire safety (e.g., threshold limit values or acceptable conditions), code equivalency becomes unfeasible (Torero, 2019).

Torero (2019) mentions that this complexity involving code equivalency, especially concerning the design for fire in historic assets, is because compliance is usually possible only when all the protective prescriptive measures have been implemented. These prescriptive requirements for historic buildings are usually a mere adaptation of the same requirements used for modern buildings, where the building's existing features, that can already provide a certain level of fire protection (i.e., construction structure, door material, etc.), are not contemplated in the design processes (Torero, 2019).

Therefore, the need to increase awareness and understanding of the current regulations and practices among the communities is urgent. Establishing a fire safety conception in which protection objectives are set holistically for a given historic building. It is also important that these concepts take into account the existing unique features, hence increasing the opportunity for alternative and innovative solutions that are both adequate and effective. This includes predicting human and natural threats by understanding the building context, for example, preventing and mitigating the destructive consequences of fire and smoke by considering that a fire could happen, avoiding societal and economical losses by integrating planning, training, and management as part of the overall fire protection.

For all the aforementioned reasons, further research must be carried out into current prescriptive and performance-based legislation as well as building regulations for historic buildings in different countries. This will promote learning from various experiences and best practices, identifying similarities and differences between countries and applications. Moreover, to improve lessons learned, the analysis and development of case studies where adequate solutions have been developed and followed by a comparison to buildings from the countries where large-scale fire incidents happened will shed light on possible effective solutions. Alternative approaches must be considered, and new methods should be studied, considering the relation between fire protection solutions and aesthetical harmony without jeopardizing the safety level. An in-depth analysis of different fire safety goals, and how they affect the fire safety design of cultural heritage overall, is also necessary.

Therefore, the present study has been performed in three stages: literature review, survey and case studies.

1.2 Aims and Objectives

The main objective of this research is to investigate, understand and explore issues related to the appropriateness of the existing fire protection solutions in historical buildings and their effectiveness in avoiding catastrophes. This is achieved by examining previous research, surveying common practices in different countries, analyzing the data collected and exemplifying it through cases studies. The objectives are to:

- Investigate the reasons and factors that make fire safety in heritage buildings so complex;
- Highlight the importance of applying fire engineering solutions combined with the main conservation principles in order to respect and preserve the uniqueness of the building;
- Show the fire expert's different perspectives of codes and practice in their country and improve the understanding about real-life challenges, experiences, and learnings;
- Analyze whether (and how) the fire safety requirements change from one country to another through a demonstrative case study.

1.3 Limitations

The major limitations are concerned with time constraints and research variables that are out of the researcher's control, such as the availability of enough data for analysis, the willingness of the contacted fire engineers to contribute to the study, and language barriers.

Moreover, although this research paper attempts to cover many of the key issues related to fire safety in historic buildings, the case study itself is limited to a few representative countries (i.e., Sweden, Belgium, Ireland, and the UK) in which the similarities and differences in the application of their fire safety codes for the same sample building will be discussed. Since not all information about the building was available, the outcome is also limited.

The results from the online survey are restricted to a small number of professionals per country that participated. Therefore, although the results provide space for discussion, they reflect the expert's own limited experience and not necessarily the whole country. Hence generalizations based on the results presented herein should be done cautiously.

There are also limitations regarding the interpretation of the code's contents due to language boundaries that can pose different levels of difficulty in research. This is because, since they differ from the author's mother tongue, making necessary the use of translator tools, some information might be overlooked or misunderstood.

One should bear in mind that the product of this research paper is more exploratory than conclusive. That is, it is not going to solve the problems and complexities involving historic buildings that have been concerning fire safety engineers and the conservation industry for decades. Conversely, it aims to explore some key aspects and issues related to this hot topic through investigations and analysis in order to gain an in-depth understanding, trigger critical thinking by showing new perspectives and further discussion on the findings.

1.4 Report structure

An overview of the structure of the remainder of the report is given below.

CHAPTERS	DESCRIPTION
Chapter 2: Methodology	*Review of the research methods employed in this paper.*
Chapter 3: Results of the literature review	*Review of literature (official guidelines, standards, scientific papers, media and investigation reports, international journal websites, and other pertinent webpages) to investigate the main issues and challenges involving fire safety in historic buildings. The state-of-art, the fire engineering and conservation principles and processes, and potential fire safety engineering mitigation solutions are presented.*
Chapter 4: Results of survey	*Investigation of the fire safety codes used in the fire design for historic buildings in different countries through the perspective of fire experts worldwide.*
Chapter 5: Historic case studies	*Review of case studies presented in three scientific papers from different countries where alternative approaches for historic buildings are used highlighting the importance of a case-by-case approach.*
Chapter 6: Practical application	*Development of a bespoke case based on an existing building with a code compliance issue as an inspiration to a practical application. The case is conducted by comparing the code requirements from different countries for the same sample building. Their similarities and differences in terms of fire safety requirements are discussed, and a qualitative analysis is carried on to propose potentially adequate solutions.*
Chapter 7: Discussion	*Comprehensive exploration of the results from literature review, survey, historic case studies and practical application; interpreting and describing their significance into the present context.*
Chapter 8: Conclusion	*Closure of this paper reiterating the main objectives achieved and communicating the importance of this study as well as the points of interest for the future.*

2. Methodology

This chapter will describe the different research methods used in the collection of data in order to present how this study was systematically designed to address the objectives provided in chapter 1, and gain a more in-depth understanding of the topic.

2.1 Literature review

This method was used to gather research data by selecting existing papers, articles, and other publications related to the main subject of this study, that is, *fire safety in historic buildings*. Keywords were used to search on the web for relevant publications, such as Google Scholar, LUBsearch (Lund University Libraries search motor), international journal websites dealing with research on the field of fire safety and protection, and national body websites to find regulations and guidelines. The key words were:

- Fire safety;
- Fire protection;
- Historic buildings;
- Protected buildings;
- Heritage building;
- Historical structures;
- Cultural heritage;
- Fire and history; etc.

These key words were also combined in different ways to try to reach and gather as many related publications as possible. Around 30 papers and 30 published documents (handbooks, guidelines, codes, and standards from different countries) were collected.

The second step was to filter the papers and articles by reading their abstracts to examine if they were indeed relevant to this research or not. Around 20 papers were filtered at this stage. Following that, another criterion was established based on the year of publication, from 2010 onwards, to select the papers for full-reading. Exceptions were made for those that, although having passed over 10 years since its publication, were believed to contain useful data. Additional publications that were referenced in the full papers and assumed to be relevant were also added to the list of literature to be reviewed later. In total 18 papers were fully reviewed for this study.

In the last stage, some of the full papers first identified were discarded afterwards and other new literature more specific-related to describe, define or help the better understanding of some key concepts were added in, to better contextualize them.

2.2 Survey methods

This research method was used to investigate the state of practice in the fire engineering field when it comes to the application of principles and processes for the design for fire safety in historic buildings. It consisted of gathering standard-related information from practitioners in the fire safety industry worldwide, in an exploratory way, through an on-line questionnaire designed to streamline the collection of data regarding the application of both prescriptive and performance-based approaches for historic buildings. The participants were invited to share their opinions, knowledge of the national regulations, and design processes derived from their real-life practices and observations. Thus, contributing to a better understanding of the big picture.

From the data collected, post-survey interviews were carried out through a follow-up with some of the participants to provide additional information related to the application of the codes and the current best practice in their country.

Online questionnaire

Through this surveying tool, it was possible to have a general view of the fire safety engineering practice in different countries. An online survey was created using Google Forms software and sent out to different fire safety consultancies around the world. The selection of email addresses was done in two steps:

1) Approach of closer researcher's network (i.e., IMFSE sponsor's companies, IMFSE Alumni, former colleagues, acquaintances, etc.);

2) Use of search engines to look for fire safety engineering consultancies around the world by typing the keywords: '*fire safety consultancy* + name of a country'. Several emails were sent to companies in the Netherlands, Belgium, Sweden, Germany, Denmark, Switzerland, France, Italy, Portugal, Spain, the UK, Ireland, Brazil, the US, Australia, and New Zealand.

The main objective was to investigate the problems related to the appropriateness of the existing fire protection solutions in these countries when it comes to historical buildings and have a general overview of how they change from country to country as well as their similarities. Therefore, the questionnaire addressed mainly national standard-related questions, with variation from multiple choice, checkbox, and open-ended questions.

The questionnaire was divided into five sections with the first section destinated to the identification of the audience regarding its gender, age, years of experience, educational background, country of work, and email address. The other four sections were regarding the organization of the regulations (Part 1), the relationship between historic buildings and building codes (Part 2), the expert's practical challenges (Part 3), and the use of alternative solutions (Part 4). The selection of the sections was done based on how the concerns about fire safety and the role of heritage buildings could be identified in the regulations by practitioners; how is the design process; and what is the level of acceptance of engineering solutions in the countries. See full survey questions in the Appendix A.

An invitation for a follow-up online interviews was sent with the same email where the experts were invited to participate in the online questionnaire. Thus, giving the respondents the chance to decide upon their willingness and availability whether they would like to contribute to both phases of the study, only one or even none. As a result, 15 practitioners took part in the online questionnaire and only one from Sweden gave an interview, which became eventually essential to identify and tailored an object for the practical application performed as part of this thesis. Two other professionals were also interviewed in different stages of this study, one from Brazil and another from Belgium. Nevertheless, since not all participants from the online survey showed readiness to take part in the interview, the results were essentially supplementary. That is, giving only a small amount of additional information to the results from the questionnaire by supporting and complementing the answers.

2.3 Case studies

This research approach was chosen to generate a more comprehensive contribution to the investigation and exploration of the topic by conveying the complex issues in historic buildings into real-life contexts. Different case studies were reviewed to show alternative solutions for different code compliance problems found when designing for fire safety in historic buildings in different countries. This allows a detailed contextual analysis in which the boundaries are identified and presented in a simplified way using the pieces of evidence defined in literature.

Following the analysis of these historic case studies, a tailored case study was created to closely examine and explore the data showed throughout this study within a specific context. Therefore, four countries were selected (i.e., Sweden, Belgium, Ireland, and the UK) for a more systematic analysis where the data collected is analyzed qualitatively using a single case design to show how the protective measures are affected when the same building is placed in different regulatory contexts. This comparative study allowed to identify the similarities and differences in the fire safety requirements among the countries. The object is a small church originally located in Sweden that had been notified by the local authorities for being noncompliant with the current prescriptive codes.

3. Results of the Literature Review

This chapter introduces the findings from the literature review arranged in different themes for a better understanding of the key issues that are going to be discussed later in this paper.

3.1 Main issues and challenges

The search and analysis of the available literature revealed that designing for fire protection for heritage buildings is complex. The issue has been hovering over the fire safety community for long years by now as fire is amongst the most severe endangerment to historic buildings (Bakas et al., 2020). This is because the impossibility of changing the building's original characteristics, such as compartmentation or adaptation of non-compliant staircases and provision of alternative emergency exits, greatly challenges the implementation of an appropriate fire safety design (Iringová, 2020).

According to the Fire Safety Guidance Note GN80 issued by the London Fire Brigade in 2015 concerning Heritage and Building of Special Interest: "The key to reducing loss in traditional buildings is gaining an understanding of the most common causes of fire. This can include accidental or deliberate causes and individual sources of ignition" (London Fire Brigade, 2015), p.4). That being said, the major challenges identified in the works of literature are as follows:

- Non-compliance with the prescriptive provisions of the fire protection codes due to the inappropriateness of the current standardized measures since they do not define sharp objectives for the protection of heritage buildings from fire; (Naziris et al., 2016; Watts, 2003)
- Increase of fire risks and fire load due to change in occupancy or change of use, where the building needs to be adapted to meet modern needs; (Li et al., 2020; Naziris et al., 2016)
- High costs of protection measures since it usually implies exceptional and high-priced fire solutions (i.e., specific materials, advanced techniques, etc.); (Naziris et al., 2016)
- Inherent fire resistance of the structure, building elements or door materials are usually not taken into account in the fire design. Similarly, they may not be permitted to be altered or tested; (Kincaid, 2018; Torero, 2019)
- The uncertainties regarding the different techniques and materials used in early times make it difficult to simulate the interaction between fire and the building, therefore, it may jeopardize the reliability of the results from the fire modeling tools; (Kincaid, 2018)
- The use of water-based fire suppression systems is still subject to concern and reluctance for owners, conservation bodies, and some practitioners due to misconceptions regarding the way these systems work. It may also cause water damage, be aesthetically invasive, or very expensive; (ICCROM, 2019; Kincaid, 2018)

- Lack of interaction between the “scientific community and the conservation industry” in developing further research on fire protection in the heritage, which results in backwardness of alternatives and conflicting ways of protecting cultural heritage; (Bakas et al., 2020)
- Need for solutions that deliver the optimal upgrade of fire safety systems in historic buildings by combining appropriate solutions, authenticity conservation, and budget limitations; (Naziris et al., 2016)
- Finding the balance between economic viability and compatibility, that is, maintaining an acceptable cost-benefit level while also ensuring the preservation of the important architectural features (Watts, 2003);
- Lack of fire safety control or careless handling of hot works during maintenance or restoration works in historic buildings (London Fire Brigade, 2015);

These problems usually induce deviations in the performance of the building where the implemented design does not respond as expected from the conceptual design. Thus, potentially resulting in undesirable fire accidents and irreversible losses to society as a whole.

3.1 State-of-the-art

In 2019, an International seminar on cultural heritage took place in Rio de Janeiro, Brazil, triggered by the fire incident in the Brazilian National Museum. This fire was a tragedy that resulted in an outrageous loss of irreplaceable objects of unique significance to human history as well as loss of the results from years of research. For this reason, the seminar focused on the discussion of fire risk management for cultural heritage, aiming to discuss ways to effectively scale down the loss due to fire. Six member states were represented, besides Brazil: Canada, Chile, Guatemala, Sweden, United Kingdom and United States (ICCROM, 2019).

The seminar also contributed broadly by sharing technical facts and knowledge from different countries with a reflection on the roles of the professionals involved in the preventive sector, in addition to the development of a trilingual recommendation document called *Declaration on fire risk reduction in cultural heritage* (ICCROM et al., 2019). The document is available in Portuguese, English, and Spanish and addresses five different topics: “legislation and policies; awareness and information; fire safety research and technology for cultural heritage; preparedness, response, and recovery; and culture of fire prevention*”* (ICCROM, 2019)para.10)

According to one of the statistics presented in the seminar by Luiz Pedersoli Jr (2019), the State of São Paulo, Brazil, and Canada have the highest average number of fire in museums per year (9/year each) when compared to the average number of fires in cultural buildings in Sweden (6/year), in cultural relics sites in China (5/year), in cultural properties in Japan (4/year) and libraries in Quebec, Canada (3/year). Giving this data, the estimated likelihood of a fire incident to occur every 30 years per heritage properties are 40% in Brazil (considering only the museums in the state of São Paulo), followed by 20% in the museums in Canada and 10% in the libraries in Quebec, 3% in China and 1% in both Sweden and Japan (Luiz Pedersoli Jr, 2019).

Other pieces of evidence presented by the same author confirmed what has already been a concern for decades: the consequences of the fire in the heritage assets go beyond the property damage. That is, it also includes economical losses, environmental impact, irreplaceable loss of unique items of humanity, loss of cultural and historical symbols to society's identity, or reduction of educational resources (when archives are also destroyed).

When comparing statistical data from Japan, Canada, and Sweden, for example, it was reaffirmed that the main cause of fires in cultural heritage is due to an electrical fault or faulty equipment, followed by unsafe practices and use of hot sources (i.e., cooking appliances, candles, hot work, smoking, fireworks, or improper storage of flammable materials) (Luiz Pedersoli Jr, 2019). The study also exposed an old but very important issue: the lack of systematic data collection in most of the countries and the consequence of this scarcity. The lack of data prevents researchers and technical bodies from developing strategies to prevent and mitigate similar fires, and improve the effectiveness of the systems used for fire protection. This is because by not tracking the fire and drawing it statistically, the real losses remain unknown, the same issues remain unsolved and fire incidents will keep happening at short intervals, consuming humanity's cultural wealth.

According to UNESCO (United Nations Educational, Scientific and Cultural Organization), most of the world cultural heritage properties are in Europe and North America (approx. 52%), followed by Asia and the Pacific (approx. 22%), Latin America and Caribbean (approx. 11%), Arab States (approx. 9%) and Africa (approx. 6%) (UNESCO, n.d.). However, these numbers do not represent the total amount of historical buildings existent around the world, since national, regional, and local authority within every country may have their own requirements for the eligibility of buildings of cultural significance at different levels.

Recent studies have highlighted the importance of investigating the fire vulnerability of each building, as well as the context in which they are inserted and their special needs, to analyze the degree to which the building physics influences its overall fire performance (Bakas et al., 2020; Torero, 2019). This might include the analysis of the increase in movable fire loads that may pose additional fire risks to a building that is changed from its original activity, which consequently implies the increase of fire protective measures (Li et al., 2020). For example, the examination of typical usages for historical buildings in China and its contribution to fire in terms of fire size showed that the higher risks are in buildings converted to venue marketing (i.e., gift shops, tea house, theatre), followed by buildings under repair works (Li et al., 2020).

Torero (2019) and Bakas et al. (2020) affirm that adequate fire designs for historic buildings can be achieved with combined efforts by developing a thorough risk assessment, and clear description of design objectives. Including the wise use of engineering methods by qualified professionals, such as modeling of materials, structures, and fire behaviors via simulation tools, fire tests, and management plans that facilitates proper design. This is because the construction techniques used in heritage buildings can significantly contribute to the fire severity since they usually have unknown voids, lack compartmentation, and may present low fire resistance of some building elements (Devi & Sharma, 2019). Therefore, it was found that when combining this information with both fire safety and conservation principles, it is possible to find the most adequate solutions that uphold any modifications to the lowest level (Bakas et al., 2020).

3.2 Fire safety engineering vs. Conservation principles and processes

It is widely known that fire safety engineering, in general, aims towards life, property safety, environmental safety, business continuity, mitigation of damage to the building and its surroundings, and reduction of economic losses (Watts, 2003). Based on these basic concepts the engineering principles are set.

The guidance on how to apply these concepts and principles can be found on the British Standard BS 7974:2019 "Application of fire safety engineering principles to the design of buildings"(British Standards Institution [BSI], 2019), which is composed by a series of Publish Documents (PDs 7974). Aiming to provide a clear framework and recommendations for the use of an engineering approach in the fire safety design for buildings in the UK, the standard yields recommendations on qualitative design review, quantitative analysis, assessment criteria, and the fire engineer's competence (British Standards Institution [BSI.shop], n.d.). All in all, the basic principles, according to BS 7974:2019, consist of:

- Avoiding fire initiation and fire growth within a compartment;
- Controlling the spread of smoke and toxic gases;
- Limiting the spread of fire and structural response;
- Detecting and containing the fire;
- Improving the effectiveness of fire service intervention;
- Ensuring safe evacuation of occupants; and
- Guiding on probabilistic risk assessment.

These principles have been incorporated in the design process worldwide and they are usually addressed in the prescriptive codes as separate components. The prescriptive-based methodology is a conventional approach that restrains the design options for complex buildings since the distinct design objectives are not explicitly addressed in the codes (i.e., historic buildings, high-rise buildings, multi-functional buildings, etc.).

Therefore, for each non-compliant component prescribed in these prescriptive-based codes (i.e., walls, ceiling, floor), an equivalent solution will be required, and this might hinder the possibilities of accomplishing a suitable and cost-effective degree of fire safety (Watts, 2003). This is because in this approach, the overall performance of the building is not taken into account, only the performance of systems individually (i.e., fire rating). While for code-equivalency, it is understood an alternative solution other than the required systems are allowed, but that these must deliver an equivalent level of performance, protection, or fire safety conditions (Watts, 2003).

The concern about the design for fire safety in heritage buildings and protected structures triggered further research in the past decades, intended to develop new methodologies to improve existing methods and assist decision-makers with the application of a more holistically-based code equivalency (Naziris et al., 2016; Shi et al., 2009; Watts, 2003; Watts & Kaplan, 2001). Most of these methodologies use fire risk evaluation tools based on hierarchy structure such as decision tables and grades (Watts, 2003). For example, Watts & Kaplan (2001) uses Fire Risk Indexing (FRI) tools to accomplish building code-equivalency; Shi et al. (2009) combines techniques such as the Analytic Hierarchy Process (AHP) with Fault Tree Analysis (FTA) to increase the credibility, reliability, and optimization of the FRI methodology; while Naziris et al. (2006) proposes a framework where he links the AHAP with a generic Selection and Resource Allocation (S&A) to estimate the costs for implementation of the protective measures.

However, when it comes to recommending which approach best contributes to the decision-making process when determining an appropriate fire safety strategy for historic buildings, there is no mutual agreement (or right answer). Some researchers affirm that although the fire risk indexing might be an elusive concept with regards to identifying and addressing subjective attributes, it still can be a more agile and reasonable approach when compared to the prescriptive-based one (Quapp & Holschemacher, 2020).

Others on the other hand, question this systematic approach stating that the methodology is inadequate since it does not define the way a risk assessment could be adapted to design resolutions, hence it does not benefit from the inherent features of the building (Torero, 2019). It also does not quantify neither the safety objectives nor the impact of the suggested alterations (Bakas et al., 2020). Therefore, should a fire incident occur, non-compliance with prescriptive codes tends always to be alleged as the main cause (Torero, 2019).

What is of unanimous opinion is the conviction that the design approach to complex buildings should evaluate their performance all together in a holistic perspective rather than individual components. That is because these buildings have usually the construction system, materials, and geometry that do not fully fit in all the categories and classifications that the prescribed solutions are designated for; hence, code-equivalency for individual components of a system might become unattainable. Moreover, practitioners, owners, and interested bodies should comprehend that achieving code compliance does not imply fire safety had been achieved and that fire safety is not solely achieved by code compliance (Torero, 2019).

All being said, a performance-based approach should strive to ensure that both fire engineering and conservative principles are combined toward the safeguard of the cultural significance of each property (Bakas et al., 2020; Kincaid, 2018; Quapp & Holschemacher, 2020; Torero, 2019).

When it comes to conservation principles and processes, on the other hand, *The Burra Charter* is a well-known document that guides the conservation and management of heritage places (Australia ICOMOS, 2013; Quapp & Holschemacher, 2020). It is produced by Australia ICOMOS *Incorporated International Council on Monument and Sites*, and it is widely used and incorporated into codes and guidelines from different countries. This is because it focuses on cultural matters concerning world heritage, as it is a non-governmental professional organization with thousands of members from around the world, and it is closely linked to UNESCO (United Nations Educational, Scientific and Cultural Organization).

The goals of the conservation principles are to *retain, restore, preserve, safeguard and reveal the cultural significance* of the heritage, and they are presented in Articles 3 to 13 (pp. 3-5) of the *Burra Charter* document (Australia ICOMOS, 2013). In summary, they are:

- Respect the originality of the building through a cautious approach by "changing as much as necessary but as little as possible (respecting existing fabric, use, associations, and meanings)" (p. 3);
- Have a multidisciplinary contribution of professionals that can contribute to the conservation of the place by using all their knowledge and skills, applying appropriate techniques and materials that "can offer substantial conservation benefits" (p. 4);
- Treat each place individually by understanding and identifying all aspects and degrees of cultural and natural significance. Conservation actions should be taken accordingly and also consider further aspects "affecting the future of a place such as the owner's needs, resources, external constraints, and its physical condition" (p. 4);
- Have a compatible use that "contributes to the significance of the place and involves minimal changes" (pp. 4-5).

Further, it is stated in the document that these principles shall be included in all conservation processes, including maintenance, restoration, reconstruction, adaptation, change of use, etc. They are presented in Articles 14-25 (pp. 6-8). In practice, it means:

- Changes should not reduce the cultural significance but when total conservation is not possible, it should be appropriate minimum and reversible;
- "Demolition of significant fabric" (p. 6) is only accepted in exceptional cases when part of conservation (minimum and appropriate), otherwise it should be preserved and protected without vanishing the "evidence of its construction and use" (p. 6);

- Reconstruction should be distinguishable. And it “is appropriate only where a place is incomplete through damage or alteration, and only where there is sufficient evidence to reproduce an earlier state of the fabric” (p. 7);
- “Adaptation is acceptable where it has minimal impact and it should involve minimal changes” (p. 7).

Since the conventional passive and active protective measures often conflict with the conservation principles, it is suggested the development of an integrated concept in which passive and active fire protection is combined with structural, technological, and organizational measures to accomplish the safety objectives for each building individually (Maxwell, 2003; Quapp & Holschemacher, 2020). Therefore, when the design process involves the active cooperation of the building’s proprietary, building authority, and heritage protection body, the outcome is expected to deliver feasible, creative, and successful solutions (Quapp & Holschemacher, 2020).

3.3 Fire Safety Engineering mitigation solutions

Although further research is still needed in terms of innovative solutions for fire protection of such buildings, it was possible to find in recent literature the efforts in compiling resourceful strategies from case studies aiming at the fire protection of cultural heritage with minor alterations to the authenticity of the building.

For instance, the use of movable smoke and fire curtains have been addressed in a number of research papers and it is claimed to be an effective alternative where compartmentation with fire-rated walls is not feasible. Since it does not require the installation of corner posts, it can be used in the compartmentation of open staircases and connected to the alarm system (Devi & Sharma, 2019). Equivalently, studies show that water mist can also be an alternative for compartmentation, acting as a curtain, as done in Windsor Castle (Kincaid, 2018).

The use of physical barriers (passive fire protection) beyond conventional walls has also been demonstrated to be a successful alternative. The application of mineral wool insulation to avoid horizontal fire spread on the wooden ceiling, for example, is pointed out as an alternative to the use of general solutions such as floorboards since the flexibility of the material allows its adaptation to the structure’s movement during a fire hence enhancing fire protection (Devi & Sharma, 2019).

Furthermore, for horizontal compartmentation, it is recommended to do interventions through the floor instead of through the ceiling whenever possible if the ceiling is an ornamental one, in order not to disturb its authenticity (Kincaid, 2018). Similarly, when sprinklers are required within the roof, water mist seems to be a suitable alternative option that will not compromise the ceiling below in case there is valuable artwork (Kincaid, 2018).

It is also recommended to use engineering tools to analyze smoke filling, temperature evolution, fire development, and structure response, for example, to support the proposal of minor alterations in the design (Torero, 2019). This is because in many historic buildings the dimensions of the compartments are large enough (i.e., ceiling height) to counterbalance the discount of some protective measures that might be too invasive to the building (Torero, 2019). Given that some of the premises' built-in features may hamper the fire development and hence allow safe evacuation of occupants, when sprinklers or compartmentation are required for life safety purposes, for instance.

Moreover, since the consequences of fire are not limited only to what the flame itself can consume but also to damages caused by heat, smoke, and water from firefighting, some recent studies, e.g., Bakas et al. (2020), Kincaid (2018), Torero (2019), make use of pragmatic methods to find feasible building upgrading alternatives. These alternatives are for the fire safety systems where fire safety management measures added to minor alterations can counterbalance the impracticable requirements of physical interventions in the buildings, while also ensuring an adequate fire safety level.

However, it is important to mention that, when researchers emphasize the need to carefully examinate the measures required for fire control and mitigation instead of solely focus on prevention of fire outbreaks (Bakas et al., 2020; Kincaid, 2018; Torero, 2019), they do not mean that fire should not be prevented. They acknowledge that ignition may be sometimes impossible to avoid as a consequence of either human or natural threats. Therefore, focusing on measures that reduce the level of damage and losses, especially when it comes to buildings with contents of cultural heritage value is key.

A more robust and successful outcome of the design for fire safety in historic buildings is more likely to be achieved when there is an integration of different specialists. That is, fire consultants, architects and conservationists working together in the development of the fire safety plan for a historic building. This multidisciplinary collaboration could have a strong influence on the designing approval process since the justifications might be more consistent and a balance between fire safety and conservation objectives is more likely to be achieved (Kincaid, 2018). For example, when the upgrade of the fire safety systems is done as part of a restoration plan that involves the upgrade of other service installations and systems, much more may be attained in terms of the level of fire safety, when compared to situations where only the fire safety upgrading is required (Kincaid, 2018).

In addition, when upgrading of fire protection systems with minor alterations to the authenticity of the building is required, it is important to evaluate conservative balance. That is, carry out a detailed survey of buildings' conditions and track its records, assess existing fire resistance, investigate the voids and analyze the existing openings, check coverage and efficiency of active systems if any, and review the management aspects (Kincaid, 2018). This is because unknown voids and existing openings (i.e., shafts, lifts) are reported to have contributed significantly to the severity of the fire in multiple incidents such as Glasgow School of Art in 2014 and 2018 (The Guardian, 2018; Warnock, 2014) and Clandon Park in 2015 (Manager & Strudwick, 2015).

Another way of upgrading compartmentation elements such as doors, for example, apart from applying translucent fire-retardant material, is to fit the door with self-closing devices, intumescent or cold smoke seals, checking the existence of any voids that might be hidden by the door frame, and seal it (Kincaid, 2018). In some cases, even replacing the whole door set when there is a robust justification for doing so, and no other solution available may be acceptable (Kincaid, 2018).

When it comes to the most effective location for detectors, since finding the best location can be an issue in terms of not being invasive to the architecture while still being effective, smoke generating machine were found to be a favorable way of validating the most advantageous position (Kincaid, 2018). The type of system, however, will surely depend on the characteristics of the building, type of combustible materials, fire load, what needs to be protected, or fire risk. For fire suppression, systems such as stand-alone or portable for water mist are reported to be already an alternative for fixed systems that requires piping installations (Kincaid, 2018).

Regarding the management strategies, some that have been successfully implemented in both Chatsworth and Historic Royal Places in England (Kincaid, 2018) are:

- Assigning the role of fire safety manager in the building to a person who is extremely familiar with the premises and its contents;
- Incentivizing human engagement through regular training for quick actions when something might compromise fire safety (i.e., obstruction of emergency routes or firefighting equipment, compartmentation door open, etc.);
- Scheduling maintenance for fire detection, alarm, and suppression systems assuring that they are well functioning; and
- Carrying out a detailed record of any system upgrading.

Finally, although many attempts and progress has been made in adopting and improving the performance-based approach worldwide, there are still a large number of countries in which only the application of prescriptive-based codes in the design are acceptable (Bakas et al., 2020).

The lack of professionals with sufficient scientific knowledge and technical expertise in assessing building performance in a fire also slows down the process of acceptance and validation of performance-based designs in countries where this new methodology is still not included in the building regulations (Bakas et al., 2020; Torero, 2019; Watts, 2003). Similarly, the lack of guidelines explaining how to achieve a certain level of fire safety through performance-based methodology makes it difficult for some professionals to implement and explore alternative solutions (Watts, 2003).

4. Results of Survey

The online questionnaire was composed of four different sections, in addition to the opening section to collect data about the correspondent, they are: **A**. Organization of regulations, **B**. Relationship between historic buildings and building codes, **C**. Practical challenges, and, **D**. Use of alternative solutions. These sections were chosen based on general questions regarding how the concerns about fire safety and the role of historic buildings could be identified in the regulations by the practitioner, how the design process takes place, and what is the level of acceptance of engineering solutions in the countries, for example.

The results are presented individually by section for a clearer understanding. In addition, there was an introductory section established to identify the participants by determining their common characteristics such as age range, gender, educational background, years of experience in the fire engineering field, and country of work.

A total of 15 participants from 7 different countries voluntarily gave their time to contribute to this research. Since there is a limited number of persons per country, the results cannot be representative of the whole country. Therefore, one shall read the results very carefully and should not make generalizations or extrapolations from them. That being said, the analysis will be conducted exploratorily to contribute to critical thinking about the current issues concerning the design for fire safety in historic buildings through the identification of triggers for reflection, to raise awareness, and to encourage further research.

It would be of great benefit, for example, to develop a survey with a greater reach of participants, including not only consultants but also product manufacturers, employees from the fire and rescue service, the government (building regulations), the conservation industry, the fire protection organizations, and students.

Figure 1 below displays the results from the introductory section of the questionnaire where it can be seen that most of the participants (57%) have backgrounds other than fire engineering, while the other part (43%) informed having a fire engineering background only. They are mostly between 30 to 50 years old (Figure 1), with extensive knowledge and expertise gathered in the fire safety engineering field over the past decades (Figure 2). This means that all of them are at the senior professional level.

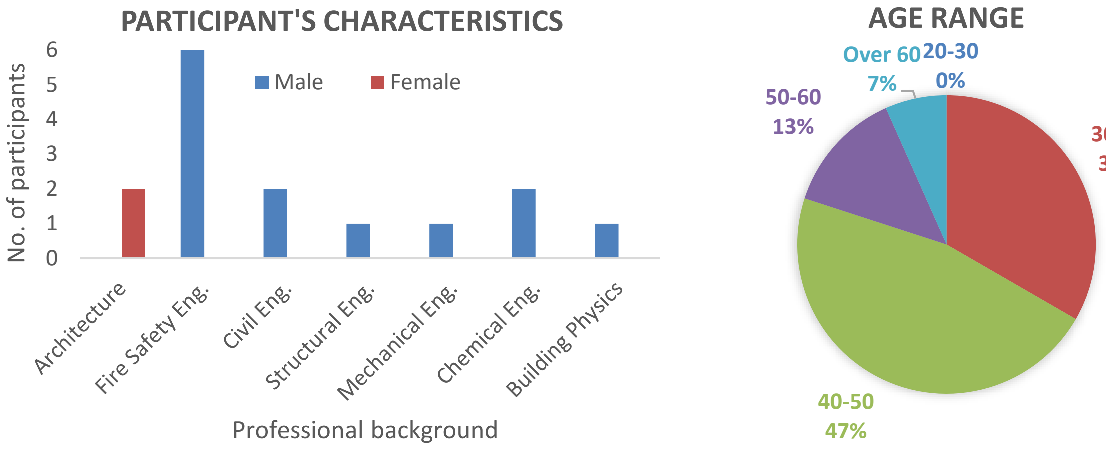

Figure 1 Illustration of the participant's characteristics regarding gender, professional background, and age range.

The countries represented by the participants are Switzerland, Netherlands, Belgium, Sweden, Ireland, Brazil, and the UK, varying between 1 to 3 participants per country, being Belgium, Brazil, and Ireland the countries with the largest number of participants (Figure 2).

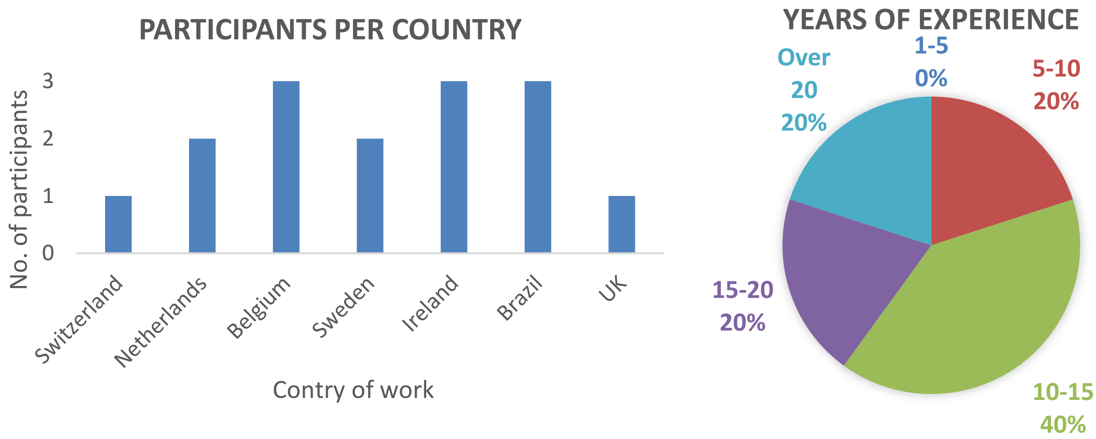

Figure 2 Illustration of the participant's characteristics regarding country of work and years of experience.

An interesting fact that could be further investigated in the future is that even experts who work in the same country as fire engineers with experience in fire design for historic buildings showed different opinions or perspectives on the same questions, even when strictly code-related. Some of them were also unsure about the different responsibilities the authorities share upon the heritage places in their country, as well as whether there are regulatory codes other than fire safety codes that address fire safety in historic buildings and whether they affect the fire design.

The interpretation of these discrepancies can be many. It might show, for example, weakness in the dissemination or clarification of sources of information among the fire community, as well as lack of proper guidance regarding the application of fire safety in historic buildings. Some countries do not have historic buildings addressed in their fire safety regulatory codes and do not have any other document or statutory recommendations to provide appropriate guidance and ensure the matter is carried out evenly across their territory.

It could also be, though, that the responsibility for the implementation of fire safety in heritage properties changes from one building to another, and therefore, each professional will have different perspectives and access to information according to their own limited experiences. Also, lack of specific knowledge from professionals, or segmentation of the consultancy services could be a reason for professionals from the same country providing conflicting answers. For instance, the person who does the fire design is not the one who submits the application or report, or searches for codes, or liaises with the responsible authorities. It could even be the case that fire safety for historic buildings are not their field of expertise.

It is important to emphasize that the analysis of the regulatory aspects of historic buildings in this paper is carried out based on the participant's responses to the questionnaire, therefore, it may not be consistent. Hence, caution should be taken when referring to these results in future studies. Note that most of the sections are composed of mixed-type questions between multiple choices, tick-boxes, and open-ended questions to allow the participant to elaborate their answers, including detailed descriptions based on their full knowledge, perception, and understanding about the matter.

Having said that, a more detailed analysis of the answers per section is presented below.

A. Organization of the regulations

When questioned regarding the responsibility for the conservation of historic buildings in their countries of work, the participants' answers were diverse, even from those working in the same country. In Belgium, for example, the minimum requirements are set at a regional level and followed up at a local level. The Flemish Organization for Immovable Heritage (*Agentschap Onroerend Erfgoed*) is the agency sponsored by the Flemish government that prepares and implements policy for cultural heritage in the Flanders region of Belgium (Vlaamse overheid, n.d.), and Monument Care Service body (*Dienst Monumentenzorg*) that advises on construction and renovation works for valuable architectural heritage in the local level.

In other countries, the minimum requirements are set at a national level through a national heritage institute such as *IPHAN* (National Institute of Historic and Artistic Heritage) in Brazil, the National Heritage Board (*Riksantikvarieämbetet*) in Sweden, the RCE (The Cultural Heritage Agency of the Netherlands) in the Netherlands, and the Historic Buildings and Monuments Commissions in the UK (with different authorities for England, Scotland, Wales, and Northern Ireland).

In the Netherlands and Sweden, the participants also mentioned the influence of real estate agencies (*Rijksvastgoedbedrijf* and *Statens fastighetsverk*, respectively) that own and manage a large part of the heritage buildings in the country, setting policies regarding maintenance and conservation of their properties, including fire safety requirements to achieve the central government goals.

In Switzerland, the only information given is that there is a committee for each county defining relevant regulations for heritage buildings in a cantonal level.

With regards to who establishes the priorities in the design for fire safety in historic buildings, the participants had the opportunity to check several boxes at the same time, meaning that the authorities in different level of the government might contribute to the determination of a set of requirements for the fire design. They also had the opportunity to write an authority not mentioned by using the 'others' option. The results are shown in Figure 3 below, where the majority (67%) answered that it is a duty of the central government to set the minimum requirements through the national regulations, followed by the regional government (53%), the local government, and the owner (40% vote for each). Also, 20% of the participants identified that the insurance company also plays a role in setting priorities in the design.

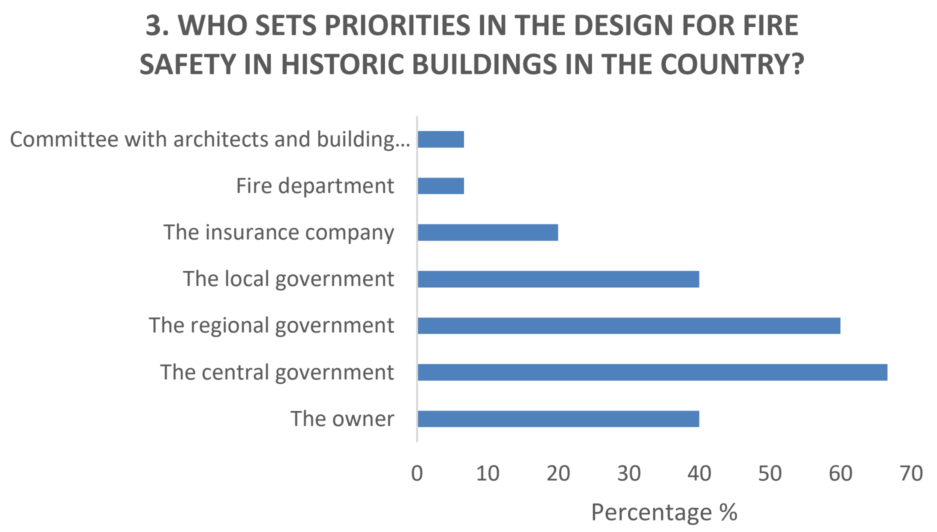

Figure 3 Illustration of the responses to who sets priorities in the design for fire in historic buildings

In most cases, the three levels of authorities (local, regional and central) play a role in the regulatory requirements for buildings, including historic buildings. The central government regulates the national building code but do not set detailed rules for historic buildings, then the regional government may set more specific requirements for heritage buildings, and the local authority, which is usually assisted or represented by the local fire brigade, may do inspections on the buildings and may set further requirements based on the risk evaluation.

In some countries like Brazil, for example, the fire brigade is a law enforcement agency that regulates fire safety at a regional level, where each state is independent and may have differences in the requirements as well as the implementation of safety measures for the same type of building. They are also responsible for inspection, approval of the fire design, and grant of the fire safety certificate so that the building can be open to the public.

In Ireland on the other hand, it was informed that the government department at the national level sets the building regulations, the local authority building control grants the fire safety certificates, the local authority planning reviews the conservation aspects of the fire design and the owner is required to apply for the so-called Fire Safety Certificate.

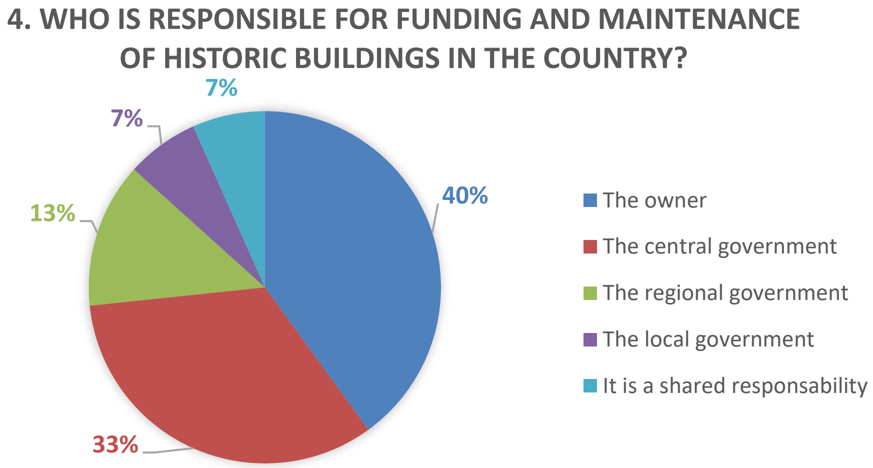

Figure 4 Illustration of the answers to who is responsible for funding and maintenance of historic buildings

When asked about who is responsible for funding and maintenance of historic buildings (Figure 4), most of the answers were that it is mainly a responsibility of the owner, but it can also be a shared responsibility. Where the government offers some subsidiary options based on the importance of the building, while the owner has to fund the remaining amount. In many countries, the government itself owns a large number of historic buildings. In Brazil, according to the information provided in the questionnaire, if a building is determined as culturally significance, the owner is required to carry restoration works and maintenance, while the government exempts it from the annual property tax as a compensatory measure.

When asked if there is any specific role for the insurance companies concerning fire safety in historic buildings, the majority answered that there is no distinguishing duty. However, they can demand a higher level of fire protection by requesting extra firefighting measures such as the installation of sprinklers or other types of fire suppression, depending on the estimated value of the building and/or its contents. In a performance-based design, for example, the insurance company may set fire safety objectives based on their requirements to provide insurance. Other insurance companies may only require the government’s certificate for fire protection (called Fire Safety Certificate in some countries) for the building and only demand further protective measures if there are specific collections of cultural significance.

When asked about the responsibility for the implementation of fire safety regulations in the country (approval, inspection, and granting of certification), most of the participants' response was that it is of regional and local governments. Where the regional authority is usually responsible for the approval and the local authority, normally represented by the fire brigade, inspects it focusing mainly on life safety. Though in some countries the fire brigade is on orders of regional and not local government.

In the UK, for example, the participant described that the local authority, or an independent approved inspector, administrates the alterations and change in use covered on the building regulations, while the fire brigade (or local fire authority) manages the buildings in use (other than domestic) that are under local legislation. In Belgium on the other hand, the owner is responsible to ensure the fire safety implementation. The fire brigade may do inspections but when there are any deviations from the regulations, the federal government is responsible for derogations for special cases through a special derogation committee.

In contrast, in order to ensure that the systems are installed in conformity with the regulations in Sweden, it was noted that a responsible person does a daily checklist of the works, and once a month a fire safety consultant goes on-site to monitor and give recommendations. This indicates the Fire Consultants have an important role in Sweden in giving suggestions and tips to the authorities. Once the works are done, the fire consultants are responsible to do a final check and inform the authorities that all the measures have been implemented as proposed. In cases where the fire consultancy responsible for the project and works are not a well-known firm or it is new in the market, the Building Authorities may hire another fire consultancy company with know-how and reliability in the industry to confirm their assessment.

B. Relationship between historic buildings and building codes

The first question aims to investigate the professional's knowledge regarding the way historic buildings are defined in their building regulations. The reason behind this question is that, according to UNESCO (2013), identifying and classifying a building as a heritage building is not as simple as it may seem, therefore, each country may define it differently. The definition usually depends on the significance of the building to each society alone and not only to humanity as a whole. The definition also depends on the environment in which the building is inserted, and how it can affect the property not only socially but also economically, thus identifying the threats and opportunities for their preservation (Ministry for Culture and Heritage, 2018).

The answers to this first question were not surprising, since most defined heritage buildings as being any building that has been placed on the national, regional, or local heritage list. While some practitioners claimed that there is no official definition in the building regulations, others said that they do not know because it usually is the Architect or the client that gives this information to them. Thus, showing that the building regulations might not define historic buildings in a clear or detailed manner. This is somehow understandable since the identification and listing of these properties are usually done by statutory bodies other than the building regulations, designated to set criteria for their eligibility to be classified as heritage (i.e., national heritage lists, monument acts, etc.).

In a follow-up question, most of the participants (60%) were negative in their answers meaning that historic buildings are not addressed in the national fire safety codes. However, a lack of consistency was observed in the answers from professionals working in the same country such as Sweden, Ireland, and Brazil. A consistent answer, though, was identified among practitioners from the Netherlands and Belgium. Switzerland and the UK had only one participant each. The negative answers in Switzerland, Sweden, Ireland, and Brazil were not justified, while in the Netherlands it was informed that there is no specification in the building regulations *Bouwbesluit 2012* and that historic building are usually treated as existing buildings in which the safety demands are lower than for new buildings.

In Belgium, it was justified that although historic buildings are not explicitly addressed in the national building regulations, other alternatives are acceptable such as NFPA books or even a completely risk-based approach. For the positive answers in Ireland and UK, for example, the practitioners informed that in the Building Regulations Part B (TGD-B for Ireland and Approved Document B in the UK), the use of alternative approaches and adherence to other guidelines or codes may be considered if the application of the regulation is restrictive or impracticable, and that historic buildings usually fall into these conditions.

In Brazil, although there are national codes for fire safety (NBR’s), the specific and detailed classification and requirements for the fire protection of the buildings are determined on a regional basis through the State’s Fire Department. Given that each State is independent of each other, some of them address historic buildings in their code and some not. Some States even adopt the technical guidance from another State when they do not have their own.

In Sweden, as a justification to the positive answer, it was informed that in general, on codes other than fire safety codes, the only mention is that the cultural heritage should not be ruined or have its value and significance altered. Therefore, allowing flexibility in the solution when the demands from the building code are impracticable.

When questioned about the accessibility of the building codes and guideline documents allowed by their country in the design for fire safety for historic buildings, only 14 out of 15 participants answered. Half of the practitioners were positive, saying that everyone has free access to the relevant codes and documents, while the other half had different opinions in this matter, see Figure 5 below.

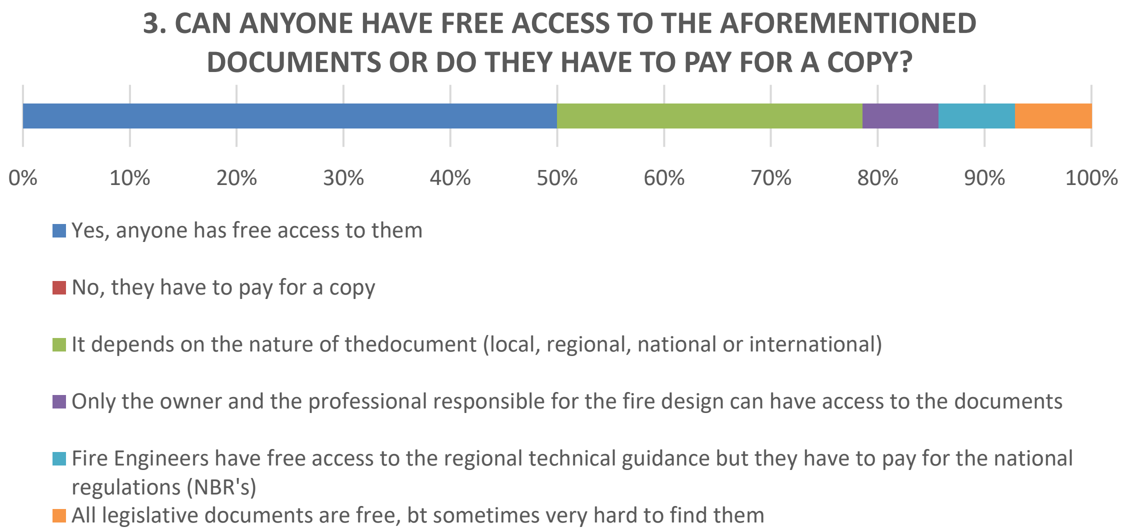

Figure 5 Illustration of the responses to whether anyone can have free access to the regulatory and advisory documents

When asked whether historic buildings are addressed in parts of the national regulatory building codes other than the one focused on fire safety, 60% of the participants said “Yes” while 40% said “No”. The aim was to investigate if additional codes other than fire safety codes influence the process of designing for fire prevention in historic buildings.

Inconsistency was found in the answers of the professionals from Belgium, Ireland, and Brazil. Nevertheless, among the affirmative answers it was informed that historic buildings are addressed in the “*Byggnadsminnseslagen*” (Building Monuments Act) in Sweden, in the “Conservation of Fuel and Power” in the UK, and in few other codes (not specified) on the preservation of historic buildings and monuments from the heritage conservation agencies in both Brazil and Belgium.

An interesting fact described by an expert in Brazil is regarding the strong influence of the heritage conservation agency on the design process for fire safety of protected buildings. It is such that, they not only follow and participate in all the process until the fire safety certification is granted, giving advice, reviewing the proposed interventions, and requiring changes, but they also have the power of not authorizing a specific intervention that may be considered too invasive. If this opposition is duly justified, they assume the responsibility for the omission or alteration of a protective measure should a fire incident occur in the future.

When it comes to the existence of differentiations or specific requirements in the national building regulations with regards to the building content, the majority (79%) answered that there are no compulsory rules that apply exclusively to building contents. Whereas the remaining 21% answered otherwise. However, in a deeper analysis it was found that there is a significant disagreement on participants from the same country, and some of them did not refer to any document where these differentiations might be present.

The last question was regarding the performance of fire risk assessment (FRA) in historic buildings. The choice for this question was because in all guidelines consulted from different countries during the literature review phase, it was mentioned that this is the most important step and should be done as the start process. The results are displayed in Figure 6 below and further investigation showed that FRA is actually not a common practice in all the countries.

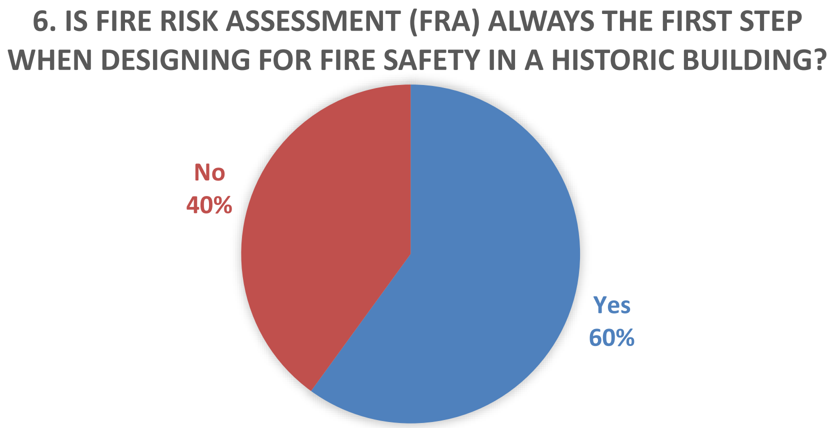

Figure 6 Illustration of the responses to whether a fire risk assessment is always the first stage in the design

Coherence is found among the practitioners from Ireland in giving the same answer ("Yes"), as well as among the ones from the Netherlands ("No"), and Sweden ("No"). Since there is only one representative person from Switzerland and the UK, their consistency cannot be compared and both answered "No" to this question. A lack of agreement, however, was identified in the answers from Brazilians and Belgians where they divided opinions between "Yes" and "No". One interpretation to this is that a risk assessment might not be mandatory or common practice in those countries, even though some professionals may adopt it as a significant part of their work process. Thus, they might have answered it based on what they do rather than what is required.

C. Practical challenges

According to the results shown in Figure 7, the most common building systems in all seven countries are brick (87%) and stone (80%). An interesting fact to mention is that in Brazil, for example, there is a particular building technique called "pau-a-pique" (wattle and daub) introduced by indigenous communities, which is not common in any of the other countries, but that poses an additional challenge to fire safety in the heritage buildings in Brazil.

Concerning the type of fire safety application for historic buildings that has higher demand in these countries, the majority affirmed it to be concerning change of use and restoration (Figure 8). Interestingly enough, although the participants could choose more than one answer for this question, these were the only two selected.

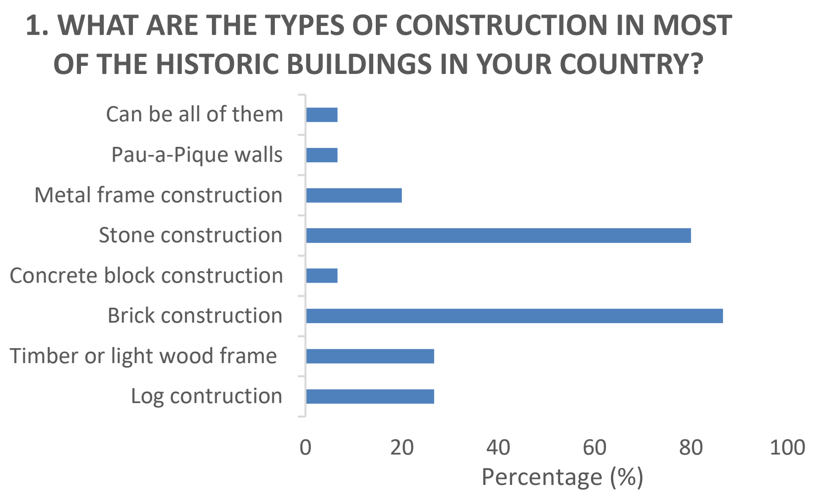

Figure 7 Illustration of the answers to the type of construction found in most of the historic buildings

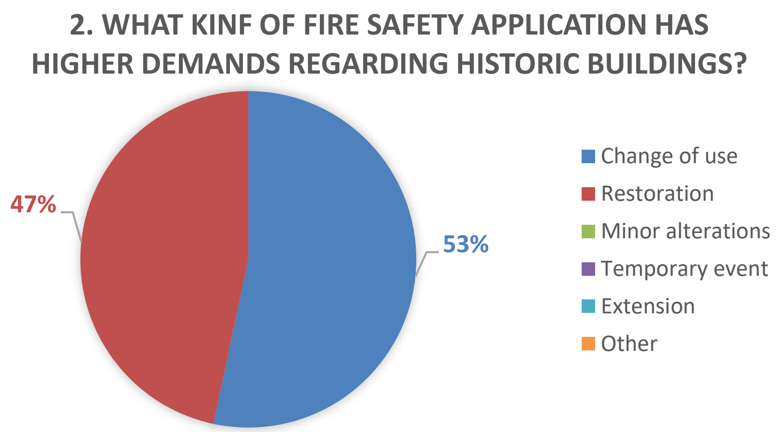

Figure 8 Illustration of the answers to the kind of fire safety application that has higher demands for historic buildings

The third question was open-ended where participants were asked to describe the process for the application for Fire Safety Certificate (FSC) for a historic building, specifying whether it depends on the building's usage (purpose group), content, construction type, or other differentiation. The answers are summarized in Table 1Table 1 below.

Table 1 Summary of the participant's answer per country referent to question 3 of the 'Practical Challenges' section

COUNTRIES	DESCRIPTION OF THE APPLICATION PROCESS TO THE FSC
Switzerland	*The process is similar to when applying for modern buildings with differentiations regarding the parties involved. The constraints and alternative solutions need to be negotiated with the Heritage Committee.*
Netherlands	*The participants did not give details about the process, informing only that the process involves several steps including building usage, number of occupants, etc.*

Belgium	*There is no such certification, although the design process for fire safety depends mostly on the use and occupancy. Following that, it is submitted for the approval of the government and the fire department.*
Sweden	*There is no such certification. No further details about the design process were given.*
Ireland	*In general, the process involves carrying out a risk assessment, reviewing the design for compliance with TGD-B, then preparing the FSC application comprising drawing and reports. And finally submitting it to the local authority for approval.* *However, the process can differ depending on the use of the building. Certain usages such as offices and private dwellings, although they still have to comply with the fire regulations, they are exempt from the application for formal fire certification by local authorities. Therefore, the purpose group will determine which requirements are relevant.*
Brazil	*The process requires the active participation of the local heritage institution since they have to approve the fire safety design prior to its submission to the local authority, represented by the fire brigade. Once submitted, the fire department revises it for approval. Once approved by both fire and heritage authorities, it is the owner's responsibility for its implementation, and the works have to be monitored by both heritage inspector and fire engineer. When the works are complete, the fire brigade carries out a final inspection and testing of the fire protection systems to grant the FSC.*
UK	*The application process differs whether it is a modern building or an existing building listed in the national heritage list (all-important historic buildings are listed). The FSC is required for buildings following the Building Regulations, which is not the case for both historic buildings and buildings in use. For buildings in use, the applicable legislation is the Fire Safety Order, in which there is no such certification as the FSC, although a fire risk assessment is required. For listed historic buildings, it is required a separate application to Listed Building Consent from the local authority and possibly for planning consent as well, since there is a special planning control for this type of buildings.*

When asked about the level of fire safety for historic buildings defined in the prescriptive and performance-based codes in their country (if any), only 13 out of 15 participants answered. The common agreement was that the level of fire safety is not explicitly defined. For those who tried to give further explanation, the answers were:

- The level of fire safety is defined by "*compliance with the rules*" in the prescriptive codes, especially if the renovation is "*large enough*" (the Netherlands and Belgium);
- "*[The level of fire safety] is similar to the regulations when the build was erected*" (Sweden);
- *"[The level of fire safety] seems to be higher than for modern buildings"*, that is, more rigorous requirements (Brazil).

One fire expert in Ireland, however, referred to an extract from TGD-B, where it states that the adequacy of the design can be defined by assessing the appropriateness of the proposed solutions through risk-based, deterministic (worst credible case) or comparative approaches (performance vs. prescriptive).

As a side note, a fire expert in Brazil noted that in his opinion the fire safety level imposed by the prescriptive regulations in the country is good enough, even though it has a lot more to improve. He added that the regulators should identify the issues related to the implementation of different purpose groups in a historic building in case of change of use, and review the mandatory requirements. This is because such differentiation and flexibility could lower the costs of restorations for the owner. He also believes that historic buildings cannot house any type of use without invasive interventions enabling sufficient conditions for the proposed occupation.

D. Use of alternative solutions

When asked whether alternative solutions are allowed in the fire safety regulations in their countries, 93% of the participants answered "Yes", while 7% answered "No". However, 7% means only one out of 15 individuals. Therefore, since this person is from the same country where other two professionals answered "Yes", it can be assumed that alternative solutions other than the prescribed in the regulations are allowed in 100% of the countries represented in this questionnaire. See detailed results in the graphs in Figure 9 below.

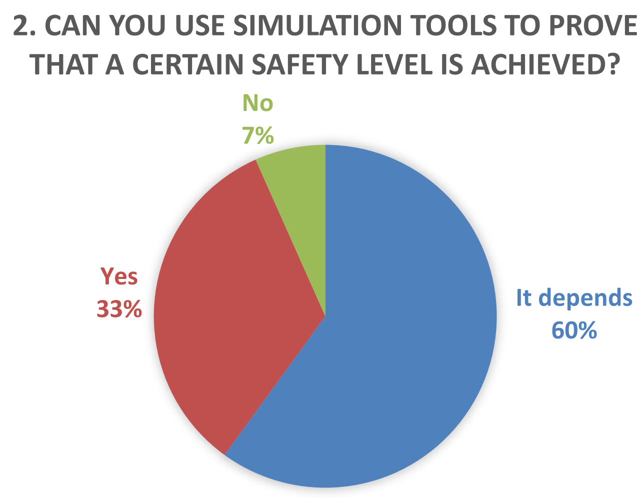

Figure 9 Illustration of the answers regarding the use of alternative solutions in the fire safety design for historic buildings

Regarding the use of simulation tools in the countries as a method to prove that a certain level of fire safety is achieved, 60% affirmed that they are allowed to use them, 33% answered that it depends on several factors, and 7% answered that it is not allowed. Among the engineering tools allowed are smoke filling, evacuation simulation models, Fire Dynamics Simulator (FDS), engineering calculations, finite elements calculations for structural elements, and (in some countries) any other tool that can prove equivalency with the regulations.

Those who answered "It depends", justified their answer in different ways. In Sweden for example, although all types of fire engineering approaches are allowed, the complete reasoning for its use has to be approved by the derogation committee. Moreover, the fire department and the government have to agree with the use of the chosen tools and may even contest the results. Therefore, they have the ultimate authority to make the final decision. In Belgium, any deviations from the main regulation (Royal Decree) have also to be subjected to a derogation committee at a Federal level for approval, while when non-compliant with rules at regional level the alternatives will be discussed with and approved by the fire department.

In Ireland, on the other hand, the acceptance of alternative solutions depends on the fire officer in charge of the revision and approval of the fire design, as some local authority fire officers might be more positive in admitting fire engineering solutions than others. In Brazil, the acceptance depends on how robust, well-justified, and comprehensive the solution is for the approving party, which has no deep knowledge about engineering methods. The respondents in Brazil added that the use of simulation models is seen as a more acceptable and reliable solution by both the heritage committee and the fire brigade.

5. Historic case studies

In this chapter, case studies from papers reviewed were summarized to illustrate how the performance-based approach, which takes into consideration the specific characteristics of a building, has been proven to be more appropriate for heritage structures in many countries.

5.1 New Zealand (Pau et al., 2019)

In this case study, the researchers Dennis Pau, Christine Duncan and Charles Fleishmann (2019) investigated a two-story historic building that underwent different restorations and changes over the years. The building was analyzed in terms of fire safety using an approach called Verification Method (C/VM2) in conjunction with the ANARP (As Nearly As is Reasonably Practicable) method. This is a compliance method for the prescriptive-based regulations for fire safety in New Zealand, referring to clauses C1 to C6 of the national building code NZBC (New Zealand Building Code) and adopted for non-compliant buildings. The method is said to allow the upgrade of the fire protection systems without jeopardizing the overall level of fire safety.

The historic building is a former residence constructed in 1989 and known as McDougall House, currently used as office and business administration. The building underwent renovations and conservation works in the past, which resulted in several changes in its functional use and its structure. However, despite having changed considerably from its original plan, there were still many unique heritage features remaining in the building of high cultural significance that ought to be preserved. So, in 2019 the building was subjected to a heritage conservation plan where compliance was required according to the NZBC.

Where it is not possible to comply with the prescriptive rules, the author applied two alternative methods allowed in the national building regulations: The C/VM2 and the ANARP. The first method uses a framework with prescribed fixed values translated into parameters for different fire design scenarios with quantitative terms for minimum performance. The second method, on the other hand, consists of qualitative analysis used to determine whether keeping the original non-protected heritage fabrics would overweight the side-effects resulting from the non-compliance. A summary of problems linked to fire safety found in the case study is as follows:

- Critical damage and cracks on many lath and plaster walls and floors, on the ornamental plasterworks' ceilings, and chimneys. Also, many walls were not aligned;
- Upgrading or addition of new systems for ventilation, fire protection, fire stopping, service, electrical and hydraulic installations were required to comply with NZBC regulation;
- Existing sprinkler system was both obsolete and very intrusive to the architecture with exposed pipes. Similarly happen to the fire rose reels;

The design scenarios in the Verification Method C/VM2 are named **BE** (Fire Blocks Exit), **UT** (Fire in Normally Unoccupied Room Threatening Occupants of Other Rooms), **CS** (Fire Starts in a Concealed Space), **SF** (Smoldering Fire), **HS** (Horizontal Fire Spread), **VS** (External Vertical Fire Spread), **IS** (Rapid Fire Spread Involving Internal Surface Linings), **FO** (Firefighting Operations), **CF** (Challenging Fire), and **RC** (Robustness Check).

The McDougall House current design was reviewed in light of the requirements in the Verification Method in combination with the ANARP principle, and it was concluded that the building satisfies the design scenarios **BE**, **UT**, **CS**, **SF**, **VS**, and **FO**. This is because the presence of sprinkler coverage enhances fire protection by limiting fire growth, thus lowering the requirements. The same applies for the design scenario **HS**, where due to the existing suppression system, the reconstructed (unprotected) original cladding characteristics could be maintained. Despite of that, a qualitative analysis was carried out to check the material's performance in terms of heat release rate, thus having confirmed that no further protective measures were required.

The design scenario **IS** represents a big challenge in terms of compliance since such elements might have an unknown composition hence making it difficult to predict or simulate its fire dynamics, nor it is possible to test or replicate them. In light of such complexity, a qualitative analysis using ANARP method was performed taking consideration to additional measures that could compensate for this noncompliance component. Thus, the fire contribution of the decorative plasterwork ceiling in the Ballroom as well as the plasterboard and timber linings on the building's walls and ceilings were evaluated.

The requirements for fire performance were examined and computational analysis was performed to support quantitatively the qualitative assessment by using fire engineering modeling software to simulate smoke generation and evacuation conditions. It also accounted for the existing sprinkler system as it works as a compensatory measure that lowers the requirements. It was concluded then, that even though the materials exceed the minimum rate for safe classification (in terms of heat flux, for example), they would not diminish the overall level of safety existent before the proposed conservation plan. Therefore, the benefits (preserving the materials of cultural significance with unknown fire performance) overweight the sacrifices (applying fire-retardant treatment or replacing the original linings for a fire-rated replica).

In the design scenario **CF**, plausible worst-case scenarios must challenge the designed fire protection systems and threaten the safety of the occupants during their evacuation. Therefore, the levels of toxicity and integrity of the structures (doors, walls, floor, leakages, etc.) in preventing flame and smoke spread were evaluated quantitatively through the review and comparison of the RSET (Required Safe Egress Time) and ASET (Available Safe Egress Time). This assessment demonstrated that should a fire start on the heritage linings; it would not interact with the occupants, hence allowing safe evacuation. Replacement and refurbishment were then only allowed and proposed for the elements extensively damaged, always following the original features and preserving other existing heritage essential features.

Finally, for the scenario **RC** the existing automatic protection system was reviewed qualitatively. An update to a system with faster response and with hidden pipes and heads was proposed. In addition to the inclusion of automatic fire detection and alarm system (the existing one was manual) connected to the doors. These doors are planned to be equipped with electromagnetic devices for smoke control in which will automatically close when the alarm system is activated. Moreover, smoke seals and certified tags are also added to these doors. Upgrade of the existing outdated emergency signage meeting the NZBC requirements was also included in the proposed fire design, although no further details were mentioned in the paper regarding to that.

5.2 **Switzerland** (Torero, 2019)

In this case study, professor José Torero (2019) chose the Bastions Building at the University of Geneva in Switzerland to illustrate the feasibility of his proposed methodological approach towards fire safety in historic buildings. This is done by considering the building's inherent characteristics to ensure both an adequate level of fire safety using minimum aesthetically invasive solutions.

Since it is only a demonstrative example of application, the only aspects of fire safety engineering that are analyzed in detail in the building are smoke spread and occupant conditions for evacuation in order to highlight the importance of using the performance-based approach in historic buildings. This is because the management of smoke can compensate for the omission of fire compartmentation in stairs and emergency routes, which is one of the most common and threatened requirements in the prescriptive codes. This compensation is proved to be effective (through the use of engineering tools) when allowing safety egress before untenable conditions are reached. However, all other aspects of the performance-based design approach are also addressed and discussed, even though not in the sample case study itself.

The diversity of the building's intrinsic features is explored throughout the paper. Investigating, discussing, and presenting the aspects regarding the building's physics in a new perspective. For example, the existing building's height can compensate the absence of sprinklers in controlling fire growth if proven through engineering calculations and simulations that flashover can be prevented or delayed in a compartment due to its volume. Thus, giving time for other safety actions to be taken such as evacuation, salvage plan, staff and firefighting interventions. Resulting in minor damages and minimum alterations.

The Bastions Building has undergone renovations twice and in one of them, the layout was changed and a series of unique stained glasses (*vitrail*) were introduced. According to the author, if a new restoration was to be considered, the compliance with the current regulations would reveal many fire safety deficiencies that could result in the removal of the unique glasswork on the corridors and fire-rating of the walls where the minimum travel distance is exceeded, for example. Other complaint solutions to meet the prescriptive requirements would include:

- Addition of new egress routes;
- Compartmentation of corridors;
- Addition of two external emergency stairs (as the monumental existing stair cannot be fully enclosed); and
- Fire resistance of structural elements.

Since some of these solutions are considered unacceptable for being quite intrusive to the architecture, an alternative approach to smoke management is proposed, starting with the evaluation of fire growth and smoke filling to calculate the time when untenable conditions are reached concerning temperature, visibility, toxicity, and egress time. A zone model is carried out and different fire scenarios were considered in the evaluation process through a sensitivity analysis of different parameters related to fire and egress. Thus, both Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) are said to had been calculated and compared.

The results showed that, even though the corridor exceeded the minimum travel distance criteria and the existing emergency routes are not fire rated, the temperature in the smoke layer will not be high enough to enable either flashover or smoke interaction with occupants. Likewise, the building contents would not generate enough heat to contribute to an increase in temperature that could threaten the structure since the ceiling height was large enough compared to the fire load.

Thus, it was concluded that the building's original structure and layout provided a safe environment even though it does not directly comply with the building regulations for fire safety. This result would also impact the decision on what to do with the wooden doors in the fire compartments. Since it was found that flashover will not occur, users will not interact with smoke and there is enough time for safe egress, the existing doors would not need to be replaced or modified. Similarly, the compartmentation in the corridor and the external emergency stairs would not be necessary, and the vitreauxs could be preserved. Therefore, active protection could focus only on compartments where there is risk of flashover and unacceptable damage/loss.

5.3 Italy (Arborea et al., 2012)

In this final case study, the researchers Alessandro Arborea, Giorgio Cucurachi, Giorgio Mossa (2012) aim to evaluate the performance-based approach in an Italian heritage building. The building was originally built as a single dwelling unit for a private family. The building was later renovated, extended, and adapted for business occupancy. Many of the original features were removed and others added. The study includes the analysis of the compliance requirements in light of current Italian regulations and validation of the protective measures through the evaluation of its influence on the tenability conditions for safe evacuation.

The design challenges derived from the constraints posed by the prescriptive regulations in Italy do not differ from the ones mentioned in other countries, where the primary objective is to reduce the impact of the interventions on historic interior fabrics and ornamental elements while also complying with the building regulatory framework. Therefore, the major concerns regard the feasibility of its restoration plan since due to its current occupancy (office), keeping in mind that the building has to satisfy not only the requirements for fire protection but also accessibility, occupational health & safety, and heritage conservation. The characteristics of the building are summarized in Table 2.

Table 2 Description of the composition of the two buildings used in the Italian case study.

Main Building	**Secondary Building**
14 m height; four stories	>4.5 m height; two stories
Semicircular main stair is the only connection to the floors (open and unprotected)	Main stair is fitted with a wheelchair lift
Basement and 2nd floor used as storage; Both with a small ceiling height.	Basement also used as storage and with a small ceiling height.
3rd floor has few loft rooms and a foyer that accommodates 50 pp.	1st floor has meeting rooms (up to 14 pp) and office rooms.
4th floor has office rooms linked by a corridor with one exit in each of the corridor's end lacking proper emergency signage. There are small-sized windows on the walls and ceilings.	

Since the study aims to account for both conservation and fire protection interests and compliant requirements, the first step was to review the existing fire safety installations. For example, the space limitation in terms of a maximum number of occupants, the fire load, and systems upgrade. Having the occupant capacity been solved, the main concern was regarding life safety since safe evacuation was compromised by the lack of compartmentation of the central semicircular stair.

As the prescriptive-codes were found not to be feasible, the Italian guidelines for the performance-based approach together with other European directives and guidelines were used to delineate the design goals and objectives. Besides the characterization of the performance criteria, the development of design scenarios, and the evaluation of trial designs to validate a solution. The objective was that all people should be able to evacuate the building safely from any floor and room in the building within or outside the room of fire origin. Based on that, many fire scenarios were investigated and conservative assumptions were made.

Three representative trial design fire scenarios were described in the paper as well as the results from the simulations. Following the fire simulations used to determine ASET, evacuation modeling for the same three scenarios were also used to determine RSET and evaluate in which of them the safety objectives are achieved. The combination of the simulation tools FDS+EVAC was used for this purpose and the general assumptions were that the exits and emergency routes are operational and unobstructed.

Account was taken for occupants' characteristics by varying the human attributes such as pre-movement time, walking speed, and shoulders width, for example. When balancing the results, it was concluded that the scenario where smoke extraction and compartmentation were combined, a moderate safety level could be achieved, yet not sufficiently enough. Therefore, for a more robust solution the authors also identified specific areas where alterations could contribute to the improvement of tenability, and suggested that additional analyses should be performed in terms of temperature distribution throughout the buildings. Further studies regarding evacuation to propose a more effective fire strategy with reliable systems were recommended.

6. Practical application

The object of this case study was suggested courtesy of Staffan Bengtson from the fire protection team at Brandskyddslaget, a Swedish fire safety consultancy firm. They conducted a study to identify the safety conditions for evacuation at Härlöv's church after it had its occupancy capacity reduced to 30 people due to the non-compliance with the local fire safety regulations, which required two exit doors installed in opposite directions.

Based on the information available, this bespoke case focuses on comparing the fire safety requirements from different countries for Härlöv's church to investigate how other national prescriptive codes would affect the building's safety design. That is, this practical application investigates how each country would perceive 'safety' for the same sample historic building. For this reason, the building floor plan was simplified and necessary information that was not provided was either defined through estimations, assumptions or retrieved from the church's public website.

The countries under comparison are Sweden, Belgium and Ireland. The choice was made based on the ease of access to information, familiarity with the building regulations and access to experienced practitioners. The similarities and differences between national regulations are presented in Table 3 for better understanding. Since the structure of the building regulations are not the same in all countries, the requirements will be analyzed in light of the fire safety principles that are translated into relevant sections in all the documents.

The second part of this practical application consists of a qualitative analysis where the church's fire safety is evaluated in light of the British guidance documents and practical advice from fire engineering experts. This is because most of the best documents found addressing not only fire safety but also risk assessment and management of heritage buildings, including traditional church buildings through the application of engineering methods for the design of buildings were found in the UK.

6.1 Description of the building

The church is originally located in a village in Alvesta Municipality, Sweden. There is clear and wide access for vehicles including public transportation. It is situated near a lake and there are two smaller constructions within the same site. Figure 10 is retrieved from Google maps and the distances are estimated based on the scale shown on the web mapping and marked up using an annotation tool.

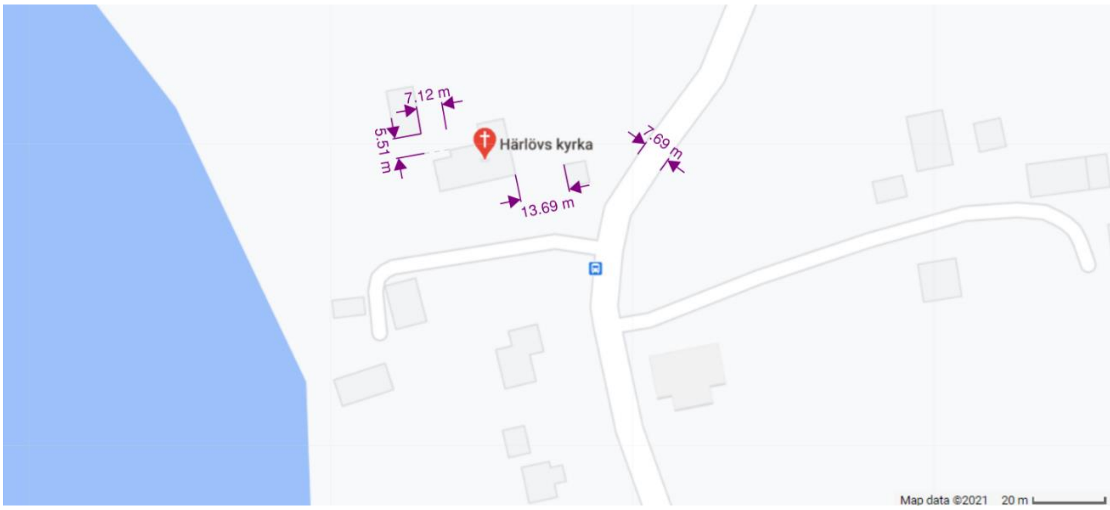

Figure 10 Härlövs church location retrieved from Google Maps (coordinates: 56.961525818152424, 14.63725945607164).

The church building consists of three compartments: a large nave (the "Church room"), an entrance hall, also named as "Armory" in the church layout, and the "Sacristy". The church room has a ceiling height of approx. 6 m and the total area of around 90 m². Since the actual dimensions of the church and the area of the other compartments were not provided, they will be estimated.

There is only one exit door, double-leaf, and with a total free width of 1.39 m. There are two windows in the entrance hall, five on the church room, one in the sacristy and one behind the altar; all assumed to have the same dimensions of 0.90 m x 0.9 m. The church has a limit occupancy of 120 people. The use of the mezzanine appears to be limited to the organist or other musicians. A sketch of the church's layout, redrawn and adapted solely for the purpose of this case study (authorized by Staffan Bengtson), is shown in Figure 11Figure 11.

In addition, it is considered that the existing church has already an automatic fire detection and alarm system designed according to SBF 110:8 (Swedish standard) with spoken evacuation alarm. The church is also provided with adequate signage on the top of the exit doors (see Figure 12Figure 12.5).

The church's interior design carries the Baroque style with exuberant paintings, sculptures, highly ornaments with enriched details like curves and deep colors transmitting movement, contrast and depth. Such characteristics combined with the uncertainty of the materials composition make it difficult to estimate a credible fire load. Figure 12 39below displays images of the interior of the church, retrieved from the Alvesta parish's website, with permission.

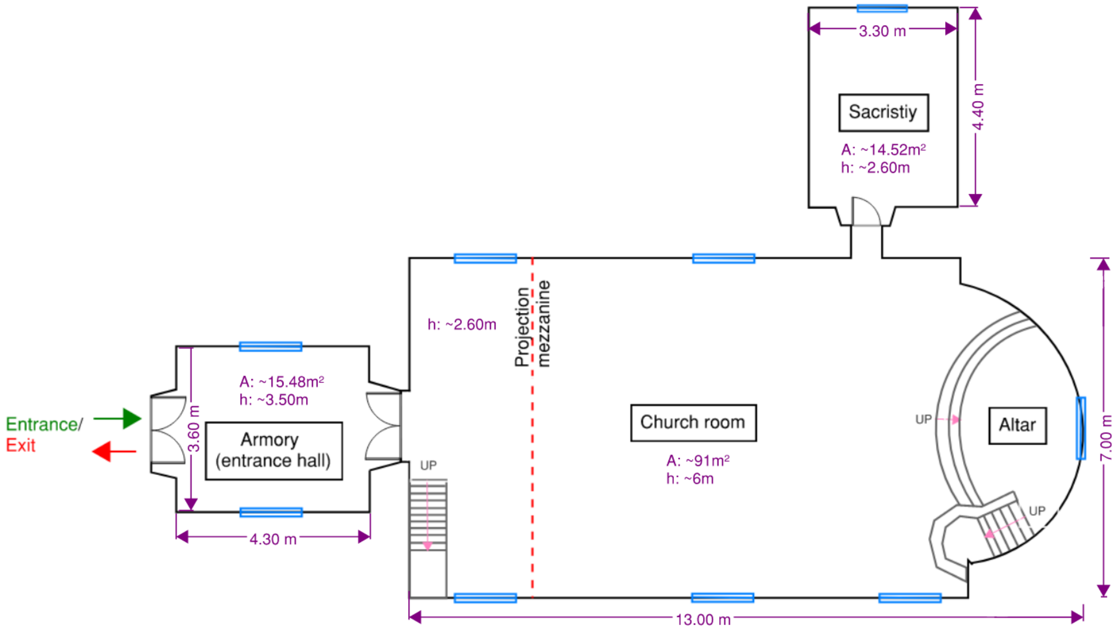

Figure 11 Sketch of Härlövs church layout based on its original floor plan provided in Brandskyddslaget's report (redrawn by Bianca Coutinho and adapted with authorization from Staffan Bengtson, here representing Brandskyddslaget).

Figure 12 Härlöv's church interior and exterior architecture. 1. View to the altar; 2. View of the church room and the mezzanine with the organ; 3. Ornamental ceiling in the church room; 4. View of the sacristy; 5. View of the entrance hall (Armory); and 6. External view of the building and neighboring construction. Retrieved from Alvesta's parish website: https://www.svenskakyrkan.se/alvesta/harlovs-kyrka. Reproduced with the permission of Elisabet Cárcamo Storm, Vicar.

6.2 Overview of the prescriptive fire codes

For the fire safety design, the Swedish National Board of Housing, Building and Planning (Boverket) offers two methods for fire safety design, the simplified and the analytical (Boverket [BBR], 2018). The simplified method is basically the prescriptive-based approach, where the building has to comply with the regulations using the solutions recommended in sections 5:2 to 5:7 of the Boverket´s mandatory provisions and general recommendations, BBR. The analytical design (BBRAD) is the approach used when either qualitative, quantitative, scenario analysis or equivalent methods are used to meet the provisions under the section 5 aforementioned (Boverkets [BBRAD], 2013).

In Belgium, on the other hand, the Royal Decree 7 December 2016 amending the *Royal Decree of 7 July 1994 Basic standards for the prevention of fire and explosion in new buildings* (Federale Overheidsdienst Binnenlandse Zaken, 2016), establishes the basic requirements and technical specifications for fire prevention in new buildings at a federal level. It is mentioned in the Royal Decree that the requirements do not apply for existing buildings, even though it could be used as directive in the absence of specific regulation that better apply (Centrum voor Religieuze Kunst en Cultuur vzw [CRKC], 2016).

However, since the Royal Decree does not legally apply neither to heritage nor to churches, codes at regional or local level are consulted. According to the CRKC documents (CRKC, 2016) and a fire expert from Belgium, the legislation more suitable in practice for Härlöv's church would be the local prevention policy, known as 'Police Codex'. This code provides rules for public behavior in the city and fire safety in public buildings. Although these codes are very similar throughout the country, each municipality (or police zone) has its own set of rules that might differ from one another at some extent (CRKC, 2016, p.4). Therefore, when it comes to fire prevention at a local level, compliance is dealt with the local fire brigade based on the local police codex.

In Ireland, there is also no specific regulation for historic buildings. After carrying out a risk assessment, the design is reviewed for compliance with the Technical Guidance Document B – Fire Safety [TGD-B] (Department of Housing, 2020) and where the requirements are deemed restrictive, alternative solutions through performance-based approach is allowed. In this case study, however, only the requirements from the prescriptive code TGD-B are examined.

In the UK, the applicable legislation for listed buildings is the Regulatory Reform (Fire Safety) Order 2005 followed by a risk-based analysis and design. Thus, the requirements from the Approved Document B are not mandatory and not added in Table 3. However, the British guidelines for risk-based fire evaluation and design for historic buildings are used as directive in the qualitative analysis to investigate more suitable solutions to the church.

It is important to highlight that, despite the possibility of applying risk-based methodologies as an alternative approach in all the three countries (i.e., Sweden, Belgium, Ireland) if strongly justified, the comparative analysis will only cover the prescriptive codes. This is because the simplified design is still the directive for code compliance in most of the countries. Moreover, it is of common practice in all countries the participation of the national heritage institute in the design process or any works involving a historic building to ensure its fair conservation.

Table 3 below summarizes the prescriptive requirements from Sweden, Belgium and Ireland in light of the fire safety principles and correspondent to the building characteristics.

Table 3 Comparison between code requirements in Sweden, Belgium and Ireland for the same church building

Fire Safety Principles [1]	***Building Characteristics***	***Building Classification & Code Requirements***		
		Sweden [2] *(Places of Assembly 2A)*	*Belgium* [3] *(Buildings Accessible to Public)*	*Ireland* [4] *(Assembly & Recreation)*
Provide safe evacuation *a) Travel distance* *b) No. of escape routes* *c) Width of exits* *d) Emergency lighting* *e) Fire safety signs*	*Single storey* *120 occupants* *Single exit* *Door width 1.39m* *Exit door opens to inwards* *Mezzanine destinated to Organ loft only.*	*a) 15 m if one escape route for class 2A. If made through window, the walking distance should be reduced to 1/3.* *b) 1 exit limited to 30 people. (Window can be used for escape and allow more people.)* *c) Door opening min. 800 mm; escape routes min. 900mm if < 150 pp.* *d) Nothing specified for class 2A. But for places of assembly 2B*	*a) 45 m from the first exit.* *b) 1 exit is up to 99 people if minimum width is 990 mm. 2 if > 100 and < 500 pp.* *c) Min. 700 mm "in case of an existing operation". (p.131) Evacuation routes min. 800 mm. (p.132).* *d) Required in the entire evacuation route, above every exit door and near*	*a) 15 m in one direction in areas with seating in rows. 18m in other areas.* *b) 1 exit limited to 50 pp. 2 if < 500 pp.* *c) Min. 950 mm if > 100 and < 150 pp.* *d) Required in the escape routes and final exit.* *e) Required in all buildings other than dwellings. (B1, p.23-52)*

		and 2C, general emergency lighting is required in escape routes and outside near the exits. e) "Small premises that are easily surveyable may be designed without exit signs", and if walking distance is max 15m. (p.61) (5.3, p.51-62)	firefighting equipment. e) Required in the emergency exit and routes. (TITEL 5, p.126, 130-133)	
Detect and contain the fire	*Existing alarm and detection system.*	*Fire and evacuation alarms and detection systems are required where it is necessary for the fire protection's design. (5.2, p.45-46) "Small mezzanine floors should be equipped with smoke alarm devices" (5.3, p.50)*	*Not addressed in the document.*	*Required only when "the fire itself may not provide adequate warning to the occupants" (B1, p.50)*
Control spread of fire and smoke	*Baroque style. Although detail of materials is not known.*	*Internal wall surfaces in escape routes at least Class B-s1, d0. Also, 30 min minimum (EI) for separating structure (Br2) (5.5, p.72, 75-76).*	*Walls in evacuate routes must have EI60. Separating structures and wooden ceilings should also be EI60. Also, false ceilings and beams or walls, columns and stair should be at least C-s2, d0. (TITEL 5, p.132, 136-137)*	*Class B – s3, d2 (European class) or Class 0 (National class) in circulation spaces and in rooms exceeding 30 m². (B2, p.67)*
Limit fire and structural response *a) Fire resistance standard* *b) Compartmentation*	*90 m² floor area* *Single storey* *No separating walls* *No special fire risks* *No shafts*	*a) 60-90 min (REI) for firewall depending on the fire load. (p.83)* *b) Firewall (REI) not needed because of small floor area (p.83). "Fire compartment classification may fully or partially be replaced*	*Load-bearing elements or fire walls should meet the requirements of "stability, flame-tightness and thermal insulation" tested in conformance with the standards BNN*	*a) 60 min minimum (REI) for elements of structure. (p.142)* *b) Not needed because of small floor area.* *c) Max. dimension of cavities in any direction = 20 m if*

c) Cavity barrier *d) Fire stopping*		*by fire resistant installations" (p.75).* *c) Same fire resistance as the separating elements. Attic divides into compartments of 400 m², and at least EI30 and class B-s1, d0.* *d) Recommendations for pipe insulation, ducts, cables, door openings, etc.* *(5.5, p.74-78; 5.6, p.83)*	*EN 13501-2 or BN 713.020.* *The document does not provide further details.* *Fire rated materials should meet the reaction to fire requirements on EN 13501.* *(TITEL 5, p.122-123)*	*the cavity is between a roof and a ceiling. Any class acceptable.* *For cavities in any other location, and with class other than Class C or Class I, the max. dimension reduces to 10 m.* *d) Recommendations for door openings, service installations, pipes, etc.* *(B3, p.74-99, 142)*
Avoid fire spread to surroundings *a) External surface of walls* *b) Permitted unprotected areas in small buildings*	*Min. distance from surrounding building 5.50 m* *Construction material is stone* *Ceiling height approx. 6 m*	*a) No extra provision if building is constructed at distance > 8m. Otherwise firewall needed. Recommendations when distance < 8m only provided for single-family houses. (5.6, p.84-85)* *b) "For windows that make up less than 20% of the affected area, fire class EW30". Or safety distance of at least 3 m for parallel horizontal unprotected surfaces. (5.5, p.78)*	*Not addressed in the document. Other documents might be consulted.*	*a) No provision when relevant boundary is > 1 m.* *b) 40% if 5 m distance; 60% if 7.5 m distance; 80% if 10 m distance. Interpolations are accepted. (B4, p.105)*
Promote effective fire and rescue response *a) Provision of hydrants or fire mains* *b) Provision of vehicle access*	*Situated by a lake* *No fire mains or hydrants* *Roads with easy vehicle access* *No areas requiring special consideration*	*a) Not needed due to small floor area.* *b) Max distance from vehicle's hard standing and the building is 50 m.* *c) Can be the same as escape route. But if firefighting team cannot access the roof with his own*	*a) Not needed due to small floor area.* *b) Not addressed in the document.* *c) Not addressed specifically on Titel 5. But on the section destinated to temporary events, it mentions a free passage of*	*a) Not applicable due to small floor area.* *b) "Access to fire service appliances should be provided to within 45 m of the principal entrance to the building" (p.126).*

c) Firefighting personnel access		*equipment, a fire-rated internal access separated from the building structure shall be provided. (5.7, p.87-89)*	*4m to the access of vehicles for emergency service (Titel 3, chapter 6, p. 81).*	*c) In low-rise buildings no further requirements are necessary. (B5, p.121-)*

Notes:
[1] Based on "BS 7974:2019 Application of fire safety engineering principles to the design of buildings-Code of practice" (British Standards Institution [BSI], 2019)
[2] Based on "Boverket´s mandatory provisions and general recommendations, BBR, BFS 2011:6 with amendments up to BFS 2018:4" (Boverket, 2011; Boverket [BBR], 2018)
[3] Based on "Code of Police Regulations City of Antwerp" (Police Codex), Title 5, applied for establishments that are accessible to the public (Antwerp Gemeenteraad, 2020).
[4] Based on "Technical Guidance Document B – Fire Safety" (Department of Housing, 2020).

As it can be seen in Table 3, although the prescriptive codes differ from country to country, their differences are not colossal. The main differences were found on requirements for evacuation. In Sweden, the maximum number of persons that can be considered to evacuate through a single exit door is 30 while in Belgium is 99, and in Ireland 50 persons. Controversially, the minimum door width allowed in Sweden is 800 mm for maximum population of 150 persons, against 700 mm in Belgium for existing buildings up to 70 occupants, and 950 mm in Ireland for occupancy capacity between 100 and 150 persons.

Comparatively, Belgian regulations seems to be either too restrictive or too lenient. This is because on one hand, it allows up to 99 people to evacuate from a single exit, and on the other hand, the requirement for minimum door width is to have at least equal amount as the number of persons allowed to use the door. That is, 1 person per cm. While the Swedish and Irish codes would consider roughly 1 person per 5 or 6 mm respectively. Therefore, giving the fact that the church's exit door is 1.39 m wide, under Belgium regulations 99 occupants are allowed, while 50 in Ireland and 30 in Sweden (the investigation of the basis of these numbers were not in the scope of this study).

Furthermore, there were not enough requirements or recommendations on the Belgian document to cover all the listed fire safety principles, as there were in the Swedish and Irish codes. However, it is important to highlight that in Belgium there is no general framework for police codex. Therefore, the fire safety requirements may change from city to city. In this case study, for example, the police codex from the city of Antwerp was used because it was the one with more information available regarding fire safety when compared to Brussels.

When it comes to limiting fire spread, both Swedish and Irish regulations require the fire classification of surface material in evacuation routes to be "B" (limited combustibility). However, in Sweden, materials are required to have little or no smoke production (s1) and no burning droplets (d0), while in Ireland materials with substantial smoke production (s3) and flaming droplets or particles (d2) are allowed. In Belgium, materials with a lower fire classification are allowed in evacuation routes. Moreover, the minimum fire resistance required for compartment walls in evacuation route is EI60 in Belgium, meaning that both integrity and insulation (EI) should be maintained for up to 60 minutes, whilst in Sweden and Ireland is EI30.

For the other fire safety principles listed in Table 3, the requirements do not differ considerably among the three countries. The main differences and implications for the fire safety design of the Härlovs church that could either threaten its authenticity or limit its use would be concerning the rules for safe evacuation. As well as for the control of internal spread of fire and smoke.

6.3 Qualitative analysis of the building

Aiming to follow an individualized approach, both guidelines and practical advice from the UK were followed. This is because, among all countries reviewed in this paper, the UK is the one that showed more advancements in the development of "go-to" documents, providing guidance and framework for the analysis of fire safety in historic buildings based on fire safety principles. These include guidelines for fire safety in traditional church buildings (Institute of Fire Engineers [IFE], 2017), risk assessment and risk-based analysis for historic buildings (London Fire Brigade, 2015), practical advice from consultant experts in the field (Barker, 2010), and statutory published documents providing framework for the application of engineering principles for fire safety solutions (BS 7974, 2019).

That being said, the qualitative analysis starts by evaluating the church's occupancy and exit capacity, followed by the investigation of the main problems, risks, and sources of fuel to be considered. Including the study of potential fire scenarios, expected growth rate and spread, and access to firefighting services.

6.3.1 Building characteristics: evacuation and exit capacities

The church's responsible person wants to have a full capacity of 120 people. The movable fire load is mainly wood and plaster. There are 10 wooden benches on each side of the church room, all interconnected with a small access door in each row of approx. 80-90cm height and 60cm width. There is only one exit door measuring 1.39 m, and a single exit route through the corridor between the benches of approx. 1.50 m (all estimations based on pictures). The ceiling height is about 6 meters. Other issues to consider in this analysis include:

- Exit capacity and time needed for full evacuation;
- Factors that could slow down the evacuation and increase the required time for safe evacuation;
- Building layout, position of the exit, potential fire risks and fire load.

The guidance for life safety strategies on occupant evacuation (PD 7974-6, 2019) was used for the analysis of the flow through the exit door and estimation of the egress time. Considering

1.3 persons/sm the average flow through doorways, and the effective width of the single exit door 1.09 meters (reducing 0.15 m in each side of the door, referred as boundary layer), the required time for the 120 persons to escape the building is around 1.41 minutes. That is, the number of persons allowed to escape through the single exit per minute is approximately 85.

In addition, the church's geometry and layout is quite simple, meaning that occupants would not have problem navigating through it and the evacuation route to the final exit is a straight line. Also, there is no obstruction on the way. However, the exit from the church's room does not give direct access to a place of safety outside the building and the occupants have to pass through the entrance hall (armory) to leave the building completely. On top of that, while the outer door opens in the direction of the evacuation but the inner door that connects the church room to the entrance hall opens inwards, hence, compromising the flow. The entrance hall is also not free from combustibles; there are wooden furniture on the side walls, papers and candles on the table at the corner (Figure 12 no. 5).

It is important to highlight that the estimation of 85 persons per minute through the exit door, which results on 1.41minutes for evacuation, corresponds only to the movement time. As for the total evacuation time both detection and pre-movement times should be added. Based on that and since the church is considered to have already a detection system, a regular fire drill is recommended to ensure evacuation starts as soon as the alarm is trigged.

Among the factors that can increase the pre-movement time are the fixed seating (restraining occupant's motion), social-influenced behaviors, and occupant's characteristics (i.e., elderly people). On the other hand, detection time can be increased if the system fails. However, it is likely that there will be people transiting through all three compartments of the church during the services (armory, church room, sacristy), therefore, a fire in its early stages would be probably detected by the someone and it may be manually extinguished.

6.3.2 Occupants' characteristics: physical conditions, awareness, period of stay, etc.

The occupants are expected to be awake, conscious and familiarized with the church layout. In addition, the probability of having people with impairments using mobility devices inside the church seems to be very low. This is because although the entrance door is wide enough, the church does not seem to have adaptable spaces to accommodate a wheelchair inside the church room, for example.

Since the church is located in a small village, the full capacity would be expected on events or on one main weekly service. The occupants are more likely to be a mix of males and females and the majority adults, therefore, the average flow used for the calculation of the exit capacity is a credible number. However, the (Institute of Fire Engineers [IFE], 2017) recommends a regular evacuation drill with the congregation to have a real estimation of evacuation time and ensure time delay is avoided by leaving without any hesitation to collect belongings or save the church's artifacts.

6.3.3 Fire Characteristics: when untenable conditions arise

Most of the contents in the church room are made of wood, with some ornaments and sculptures with plaster. It is hard to identify from the pictures if the wall is covered by lining or painting only. There is some upholstered furniture and a wooden piano by the altar and seat cushions on the wooden benches. There are also candles throughout the compartment and books (bibles or hymnaries) in each bench row. However, although the fire load seems to be high, the probability of a fire to grow unnoticeable and reach untenable conditions while the church is occupied, in either full capacity or not, is low.

The same can be assumed for the entrance hall, where the predominant fuel source there is made of wood. That is, although the fire growth rate is considered fast for wooden furniture, for instance for a plywood wardrobe (Karlsson & Quintiere, 2000), for a fire to develop in this material, the ignition source has to be quite intense. The existing fire sources in the entrance hall do not generate such a high heat output (only few candles and a compact panel radiator). The sacristy has the walls and ceilings covered by a combustible lining material (some kind of fabric or decorative foil), which could potentially be ignited and then lead to a rapid flame spread in the compartment. The room also contains candles, table clothes, books, and wooden furniture that may turn it into a very hazardous compartment should a fire occur unnoticeable. Thus, the sum of the aforementioned factors aligned with the small dimensions of the compartment could lead to flashover, if not detected in its early stages. However, it is very unlikely that occupant's life is at danger if the church is occupied or being used for any kind of activity, since they are likely to evacuate before this extreme fire condition is reached. The major risks would then be related more to the protection of the historic contents than to life safety, as the church is already equipped with fire detection and alarm system.

6.3.4 Potential fire scenarios

As stated in (BS 7974, 2019): "In theory, several factors can contribute to the fire scenarios, but in practice the contribution of many factors is insignificant". Therefore, care should be taken when selecting plausible potential fire scenarios for historic buildings, accounting for their inherent features and social context that can limit the fire size or reduce its likelihood.

For example, the (BS ISO 16733-1, 2015) provides guidance for the selection of design fire scenarios and gives ten examples to be accounted for in the engineering analysis: fire blocking exit, fire in an unoccupied room, fire in a concealed space, smoldering fire, horizontal fire spread, vertical fire spread, rapid fire spread in the surface linings, challenging fire for the firefighting team, challenge fire for life safety, and unreliability of safety systems. All these considerations should be evaluated carefully in the development of the credible fire scenarios when carrying out a performance-based design for complex buildings such as historic buildings. However, since the bespoke case is a small historic church with simple geometry with low occupancy capacity and no special hazards (i.e., chemical substances), the qualitative analysis can be simplified.

Fire blocking the exit

For a life safety perspective, the most threatening fire scenario would be a fire blocking the single exit. For such conditions to occur, it should be an ultra-fast developing fire which is unlikely due to the nature of the materials present in the entrance hall, unless if set up criminally. But an arson attack is also unlikely to happen, especially in populated churches located outside the main towns and cities (Institute of Fire Engineers [IFE], 2017). However, all sources of fire and combustible materials no matter how small they are should be removed from the entrance hall, such as candles, papers and books. Moreover, garbage bags or any kind of debris should also be put far away from the exit.

Fire in an unoccupied room

A fire starting in an unoccupied room, growing unnoticeable and threatening an occupied room, on the other hand, is a plausible scenario, since the sacristy has a potential amount of fire sources and burning fuel packages. The combustible lining on walls and ceiling can cause a rapid flame spread to happen. This scenario is most likely to happen when the church is not fully occupied because during services the sacristy is usually used by clergy multiple times. This fire scenario would then pose a higher risk to the property than life safety, meaning that active fire protection measures could be justified for the safeguard of the historic artifacts and integrity of the architecture.

Smoldering fire

In general, a fire involving solid materials grows fairly slow when not composed by flammable materials, liquids or gases (BS 7974, 2019). Thus, in a partially of fully occupied church of approximately 7 m x 13 m, where the occupants are conscious and awake, and no flammable material is handled, any fire or smoldering fire would be rapidly smelt or the smoke seen, even if starts in and adjacent room. However, preventive measures should be taken to prevent any probability of ignition, such placing combustible materials and furniture remote from the electric panel radiator and keep candles distant from potential fuels. Also, staff should regularly carry out detailed inspection before closing of the church to make sure all electrical appliances are shut off and all candles are properly extinguished.

Challenging fire

A challenging fire for both firefighting team and life safety would be a fire starting between the ceiling and the roof as what is in there is unknown. Should an electrical fault occur in this area, it might lead to the ignition of combustible materials close to it, for instance cables, thus growing unnoticeably and igniting the wooden roof structure. Therefore, all service installations of the church should be inspected, also checking also the need for fire stopping or cavity barrier.

Robustness check

To ensure a robust design, a more detailed study accounting for the failure of the alarm and detection systems and human perception, while evaluating the fire dynamics and smoke movement within the church must be performed in order to ensure all occupants can leave

the premises before untenable conditions are met. This could be done by, for example, using simulating models to assess the fire dynamics in the sacristy compartment since it has a potential for flashover to occur once the fire is well stablished. The study would provide a better estimation of the time at which smoke and heat would be as such to spread to the church room and have effect on safe egress of occupants or structural stability.
Noting that this would be an extreme and rare case, all parties should be included in the decision-making process. Thus, having achieved the life safety objectives, the fire safety measures can be focused on the protection of the building contents, internal architecture and structural stability.

6.3.5 Accessibility for the fire and rescue team

The church location, as it can be seen on Figure 10, provides favorable conditions for the operation of firefighting team. The guidance and matters of concern listed on (PD 7974-5, 2014) were followed in this qualitative analysis. Vehicle access to the church is done through the main road and the fire service appliances can have access within 5 meters from the perimeter of the building. The lake situated behind the building's site can also be used as water supply.

The main construction material of the church is stone which inherently provides certain structural stability when subjected to a fire. Windows could also be adapted to be used both in occupant's evacuation and firefighting access. On top of that, the closest fire station seems to be only around 16-17 minutes away (Alvesta Brandstation), although detection, reporting, preparation and operational times should also be taken into account when estimating the firefighting intervention time.

Furthermore, when it comes to both loss and damage control, a salvage plan is recommended in order to provide the fire and rescue team a guidance for intervention and increasing its effectiveness. Therefore, as part of fire strategies the fire evolution and the expected time for the fire service response should be taken into account for the estimation and management of loss and damage. As well as for the decision on the implementation of mitigation solutions such as suppression systems if found deemed needed.

6.3.6 Potential Solutions

A summary of the potential solutions for the church's particular issues based on the fire engineering principles are listed in the Table 4 below for a clearer understanding.

Table 4 Summary of the potential solutions proposed after the qualitative analysis done in the Härslövs church.

Fire Safety Principles	***Church's main issues***	***Potential Solutions***
Provide safe evacuation	*Lack of alternative exit.*	*Regular fire drill with congregation to better estimate evacuation time and avoid factor that may cause delay.*
a) Travel distance	*Travel distance longer than the maximum*	
b) No. of escape routes	*required in most of the prescriptive codes for*	*Regular training of clergy/staff to immediate response to alarm signal*

c) Width of exits *d) Emergency lighting* *e) Fire safety signs (already provided)*	*buildings with a single exit (~15 m).*	*or fire evidence, implementation of evacuation and salvage plans, use of manual firefighting equipment and liaise with fire and rescue team.* *The inwards openable door should be held open during church's operation and evacuation route kept free from obstacles or combustible materials.* *Provide emergency lighting on exits (there is already wireless smart systems in the market).*
Detect and contain the fire	*Large cavity between the church's ceiling and roof may pose additional risk.* *Check firefighting team accessibility to this cavity space.*	*Inspection of the services and installations, and the potential fire risks in the cavity. Implementation of adequate solution (fire stopping, sealing, insulation or fire barrier)* *Review of the current detection and alarm system to ensure its reliability in detecting a fire in its early stages.* *Provide fire detection and alarm system in the void space between ceiling and roof. Careful should be taken in selecting dust-resistant detectors to avoid false alarms.* *Staff training to use fire extinguisher on small controllable fires.*
Control spread of fire and smoke	*Combustible linings on the sacristy walls and ceiling – and possibly on the walls of the church room* *Ceiling on church room composed by timber paneling with ornaments and valuable paintings* *Sprinklers or firefighting team extinguishment through the roof can be disruptive to the artistic painting underneath the ceiling*	*Investigate the possibility of upgrading the fire performance of the wall linings and timber by applying translucent fire retardants that do not alter the original surface.* *Another alternative would be the implementation of fire suppression systems, although this solution would be more expensive. Water mist nozzles are available in the marked for a minimally invasive aesthetic solution and less water damage.*

Limit fire and structural response *a) Fire resistance standard* *b) Compartmentation* *c) Cavity barrier* *d) Fire stopping*	*Tracking voids that can quicken fire spread and endanger structural stability without disrupting the walls' linings, or developing dampness problems*	*Consult a specialist in restoration of heritage buildings regarding the possibility (and the less disruptive technique) to remove the walls' linings for inspection or installation of fire stopping measures.* *Ensure availability of firefighting equipment (manual extinguisher's, blankets) for the appropriate fire class, and adequate staff training to help preventing uncontrolled development of small fires.* *Ensure fire services access to the local water resource for effective fire control should an incident occur.*
Avoid fire spread to surroundings *a) External surface of walls* *b) Permitted unprotected areas in small buildings*	*Not really an issue in this building since there is no combustible material on the façade. The church is made of stone and the surrounding constructions are more than 5 meters away.* *However, an extra study regarding the impact on the environment should a full developed fire occur could be interesting to avoid fire spread to the open land.*	
Promote effective fire and rescue response *a) Provision of hydrants or fire mains* *b) Provision of vehicle access* *c) Firefighting personnel access*	*Not really an issue since the vehicle access and water resource are not limited. Moreover, there is a rescue service station less than 18 min away.*	*To ensure effectiveness of fire rescue team intervention, it is important to have a clear fire documentation (access, layout, salvage and damage plans), as well as liaison with the nearest fire brigade for a planned action.*

7. Discussion

Findings from recent literature show that the main cause of fire in historic buildings has been the same for decades (e.g., electric failure, lack of maintenance, and unsafe handling of hot sources), and that most of the issues concerning non-compliance are already widely known but still unsolved. These two points combined together might be what makes this topic so complex. Part of this complexity is due to the insistence on using modern inflexible codes with generalized pre-accepted solutions in buildings that need to be treated individually due to their peculiarities. Nevertheless, although one could say that the solution for this problem is obvious through the standardization of risk-based approach across the world, in practice the implementation of performance-based codes is not that simple. This is because the incorporation of analytical tools in the design for fire in a given national code needs to be supported by clear guidelines, codes of practice, and provision of specific professional qualification.

To support this discussion, the online survey showed that in countries where the prescriptive approach prevails, the acceptance of alternative solutions involving performance-based engineering methodology is limited to the domain knowledge (or comprehension) of the person in charge of the design approval. This is understandable, because in the absence of national guidance on the assessment of engineering-based solutions, choosing the regulated legal practice seems to be the right and safer decision. Although the participants also informed that the use of simulation tools has a better acceptance rate if the application of such tools are well-justified. Furthermore, the lack of professionals with sufficient scientific and technical know-how to evaluate the performance of the building in fires, also delays the acceptance process.

Literature shows that there is a conflict between the desire to maintain the building characteristics untouched, and the desire to upgrade or improve the fire safety measures in the heritage to avoid unacceptable losses. The combination of the inflexibility of the modern codes with the restrictive conservation requirements poses additional challenges since in many cases it is impossible to comply with regulations without changing or disturbing the building's original characteristics. Having said that, a suggested way to solve this problem would be to establish clear combined objectives in all steps of the design process, which has been proven to be attainable only when using a performance-based approach.

Another way to deal with the aforementioned conflict, and this should consider a long-term investment, is through events like the one in Rio de Janeiro in 2019 where practitioners from various departments of the heritage sector worldwide shared experiences, called for action and raised awareness. However, much more needs to be done, such as increase research contributions, develop funding strategies for funding sources and develop efficient management strategies to ensure that effective solutions are provided to buildings of special interest on a case-by-case basis. Such actions seem to be the key to bigger changes.

Mitigation solutions found in the literature and compiled in this paper showed that maintenance and management are key for the implementation of an effective fire safety strategy. Various technical solutions, such as elements, equipment and systems that are reversible, wireless, movable, smart-activated, can be hidden or removed without compromising the authenticity of the building, can already be found in the market. The literature study also emphasizes the importance of using engineering tools that help to predict fire behavior, smoke movement, structural response, and smoke interaction with occupants in assisting decision-makers to come up with the most appropriate solution. The overall recommendation from the literature study is to combine management, training and maintenance, and to focus not only on preventing the outbreak of a fire, because this can be impossible, but focus on measures to control the fire and minimize losses.

The complexity concerning fire safety in historic buildings also involves the traditional debate about the use of code-equivalency, since it is hard to achieve an equivalent level of safety when the prescriptive codes have no clear design objectives for historic buildings. This is because in many cases, the equivalent solutions seem to be an adaptation of the existing unfeasible requirements that do not benefit from the building's characteristics. Consequently, inherent features that may already deliver some level of fire resistance and lower restrictive requirements cannot be taken into account. On top of that, non-compliance will always be deemed a problem, even when code-equivalency is applied. Therefore, a solution to the non-compliance problem, found both in the literature and in the historic case studies presented, is to use a risk-based approach in which uncertainties, special conditions, building and occupant's characteristics can be considered in the fire safety strategy process.

The historic case studies help to improve the lessons learned and to understand how fire safety design in heritage buildings have been conducted in different countries, e.g., New Zealand, Switzerland and Italy. They show that the performance-based approach, which accounts for the specific characteristics of the buildings, is flexible, more appropriate and effective in different contexts, thus being widely applicable when designing for fire safety in historic buildings. Further, the importance of investigating the vulnerability of each building within their individual context is illustrated by the case studies.

Among the issues revealed in the online survey is that historic buildings are not addressed, neither in the fire safety codes nor in other national regulatory codes, but only in documents issued by the heritage conservation agencies where not all aspects of fire safety are covered. Also, most of the countries seem not to have compulsory rules exclusively for building contents, the fire risk assessment is not always the first step (contradicting the various relevant guidelines found from the UK, for example), and change of use seems to have higher demand over restoration. On the note of change in use, literature shows that the more a heritage building changes from its original use, the higher the fire risks and hazards are likely to be since the movable fire load tends to increase to adapt to the new activities. Thus, culminating in either more restrictive protective measures or more invasive solutions.

The respondents from the survey also confirm what has been addressed in the literature: no historic building is the same. Even when they appear to have used the same construction material or were built in the same period of time in history, they are still unique. For this reason, many variables should be considered when developing a fire safety strategies and design objectives to the building, such as social context, geographic location, environment, layout, contents, physical changes over time, technical factors, conservation requirements, among others. These variables play a fundamental role in the effectiveness of the fire protective measures proposed, not only in terms of operability but also related to financial costs. This final point is particularly important, since one of the problems described by the responders of the questionnaire was the fact that the mandatory code requirements usually make renovation too onerous for the owner.

The survey also reveals that professionals from the same field that deal with historic buildings do not always share the same point of view even when related to standard. This might be expected since the definition of historic buildings also differs from country to country. Also, the fire regulations are generally not clear enough or do not address historic buildings, usually threating them as an existing building or places of public access. The perspective of professionals on how the level of fire safety is defined in their country also differs, from being compliant with the rules, being similar, or at least not reduced from when the building was erected, to even being perceived as higher than the level required for modern buildings.

This is why it is so relevant to analyze and understand how the application of prescriptive requirements is framed within the boundaries of different national legislations, and how they could affect the final fire design of the same given building. Thus, a comparative study with a practical application was performed in chapter 6 to conduct an in-depth analysis. The outcome led to the conclusion that, through a risk-based qualitative analysis in the practical application, the church's full capacity of 120 occupants could be possible even though the current modern codes suggest otherwise.

This is because, giving an individualized analysis and flexible approach to a building of special interest such as this church, it is possible to find alternative solutions that ensure life safety without jeopardizing both the level of fire safety and the building authenticity and use. Although a similar approach could be used in other countries, it is true that this qualitative analysis is not conclusive nor exhaustive. In the process of developing a fire design in real life, more evidence using engineering tools to measure the results quantitatively should be presented to ensure the robustness of the solutions proposed.

It was accentuated, however, both through the literature review and the outcome from the practical application, that management strategies have indeed a significant impact on fire prevention and mitigation, playing a determinant role in the overall fire safety strategy. These management strategies include carrying out a fire risk assessment, regular inspections, fire drills, and developing a detailed fire documentation, for example. Not to mention the recording of any small fire incidents and building maintenance works. Further, when occupancy capacity is above 50 persons, it is recommended the aid of stewards on the exit doors, maintaining the inward door ready to be opened in an emergency, and the corridor free from obstructions.

Windows could be used for evacuation in case a fire starts near the church's exit door, despite the low likelihood. In fact, this alternative is only allowed for public buildings in the Swedish prescriptive codes, and the church's windows are compliant with the minimum requirements: side-hung on a vertical axis, possible to work without a key, clear opening of at least 0.5 m x 0.6 m and windowsill of max. 2 meters. In the Irish and British regulations, windows can only be considered for evacuation in dwelling houses, while not addressed in the Belgium codex.

Regarding protection of building contents, besides the implementation of a management system and staff training, the installation of suppression systems could be an option for reducing the damage if a fire occurs during the night or when the building is unoccupied. However, since this is not addressed in the prescriptive codes due to the size of the building, a more detailed investigation should be made to enable an accurate decision concerning whether the contents within the building requires the investment on fire suppression or not. This decision should involve the participation of all relevant stakeholders and be aligned to the specific design objectives, where priorities are given based on stakeholders' goals, financial resources, and conservation demands, for example.

As it can be seen, a risk-based analysis was revealed to be more appropriate to buildings that are not specifically addressed on the prescriptive fire codes, allowing the non-compliant issues of such complex buildings to be resolved with more flexibility, considering all the safety measures as a holistic system. This is because, while the prescriptive codes use the same engineering concept to deliver a more generalized strategy, divided per building categorization and applicable for a wide range of occupancies within a certain categorization, their application does not allow sufficient consideration of the building's individualized context. The building's particular features combined with tailored fire management strategies, for example, could compensate some of the unfeasible compulsory measures.

Further, the holistic analysis using an engineering approach delivers a more logical, optimum and effective set of provisions, where different credible scenarios are considered in different situations for different buildings. Consequently, the contribution of the fire protection measures intended to meet the primary safety objectives can be evaluated, and eventually some specific requirements that would be mandatory under the prescriptive codes can be reconsidered, given that the whole system is proven to deliver the required fire safety level.

8. Conclusions

It was mentioned in the beginning of this paper that the main objectives of this research were to investigate, understand and explore issues related to the appropriateness of the existing fire protection solutions in historical buildings and their effectiveness in avoiding catastrophes. These objectives were achieved through the literature review by presenting the complex relationship of historic buildings with fire, the different vulnerabilities, natural and human threats and the propensity of a fire to occur, by showing the application and justification of alternative solutions used in different historic buildings worldwide, and by conducting a tailored case study.

The real-life practical challenges when designing for fire safety in heritage structures in different countries were explored through the elaboration and analysis of an online questionnaire where 15 participants from 7 different countries shared their experiences. Overall, the answers from the survey did not differ tremendously regarding the building control system and how regulations are organized. The answers indicated that there is a lack of differentiation on the fire safety objectives for historic buildings in the countries, and the majority do not even have historic buildings addressed in the national fire safety codes.

The understanding of the issues concerning heritage buildings was also improved through the development of a practical application on an existing historic building using a risk-based qualitative analysis, and through the investigation of historic case studies. Thus, making possible to explore the different strategies and variables that can be used to achieve a certain design objective or performance-based criteria. While the case studies showed that the original layout of the building may restrain the implementation of appropriate fire safety measures, it may also happen that the best solution for some cases is not to allow such activity to take place in a specific room or building when the interventions required are deemed detrimental to its cultural or historic significance.

It can then be concluded that, in order to deliver a more suitable and respectful fire safety design for buildings of special interest, it is of paramount importance to critically evaluate the conditions and hazards of each building on a case-by-case basis. The fire safety objectives should be clearly identified and the study should consider the different needs and constraints, pondering costs and benefits and using scientific-orientated knowledge to meet the fire safety objectives. However, this approach would imply also the need of more qualified professionals with not only scientific knowledge but also relevant experience to use engineering judgement when there is not enough scientific or historic evidence. In addition, more research should be carried out to provide more evidence and improve the range of alternative solutions that are minimally invasive while highly efficient.

Therefore, striving for adequate and effective solutions that respect the uniqueness of the building should be a combined responsibility of paramount importance, involving not only the fire safety engineers and the conservationists, but also experts from fire protection industry, academia, and the government. This, of course, would demand time to provide research contributions, gather financial resources, engage the community, integrate new concepts and responsibilities, and to enforce new regulations that ensure the provision of effective solutions to historic buildings.

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As John Lennon has already written:
"*You may say*
I'm a dreamer
But I'm not the only one
I hope someday
You'll join us
And the world will be as one".

So, let us keep making a difference. Let the next phase begin!

References

Antwerp Gemeenteraad. (2020). *Code van politiereglementen stad Antwerpen (politiecodex)*.

Arborea, A., Cucurachi, G., & Mossa, G. (2012). *Performance-based fire protection of historic buildings in the Italian perspective: a simulative approach*.

Australia ICOMOS. (2013). *The Burra Charter : the Australia ICOMOS charter for places of cultural significance 2013*. Australia ICOMOS, International Council on Monuments and Sites.

Bakas, I., Georgiadis-Filikas, K., & Kontoleon, K. J. (2020). Treasures gutted by fire. Fire safety design awareness as a consequence of historic building accidents and disasters. *IOP Conference Series: Earth and Environmental Science*, *410*(1). https://doi.org/10.1088/1755-1315/410/1/012113

Barker, P. (2010, June 1). *Fire safety and heritage buildings*. https://www.thenbs.com/knowledge/fire-safety-and-heritage-buildings

Boverket. (2011). *Boverkets föreskrifter om ändring i verkets byggregler (2011:6) – föreskrifter och allmänna råd, BFS 2011:26*.

Boverket [BBR]. (2018). *Boverket´s mandatory provisions and general recommendations, BBR, BFS 2011:6 with amendments up to BFS 2018:4*. https:// www.boverket.se/globalassets/publikationer/dokument/2019/bbr- 2011-6-tom-2018-4-english-2.pdf

Boverkets [BBRAD]. (2013). *Boverkets författningssamling BFS 2013:12 BBRAD 3*.

British Standards Institution [BSI]. (2019). *BS 7974:2019 Application of fire safety engineering principles to the design of buildings-Code of practice*.

British Standards Institution [BSI.shop]. (n.d.). *BSI. shop: BS 7974:2019 Application of fire safety engineering principles to the design of buildings. Code of practice*. BS 7974:2019. Retrieved March 6, 2021, from https://shop.bsigroup.com/ProductDetail?pid=000000000030353758

BS 7974. (2019). *BSI Standards Publication Application of fire safety engineering principles to the design of buildings-Code of practice*.

BS ISO 16733-1. (2015). *Fire safety engineering. Selection of design fire scenarios and design fires. Part 1, Selection of design fire scenarios.*

Centrum voor Religieuze Kunst en Cultuur vzw [CRKC]. (2016). *Wet-en regelgeving inzake veiligheidszorg Inleiding*. http://www.werk.belgie.be/welzijn_op_het_werk.aspx

Department of Housing, L. G. and H. (2020). *Building Regulations 2006: Technical Guidance Document B - Fire Safety*. https://www.gov.ie/en/publication/263ee-technical-guidance-document-b-fire-safety/

Devi, K. S., & Sharma, T. D. (2019). Innovations in conservation of heritage museums and libraries from fire hazards. *AIP Conference Proceedings*, *2158*. https://doi.org/10.1063/1.5127129

Federale Overheidsdienst Binnenlandse Zaken. (2016). *Koninklijk Besluit Van 7 Juli 1994 Tot Vaststelling Van De Basisnormen Voor De Preventie Van Brand En Ontploffing Waaraan De Gebouwen Moeten Voldoen*. https://www.besafe.be/nl/wetgeving/koninklijk-besluit-7-december-2016-basisnormen-voor-de-preventie-van-brand-en-ontploffing

ICCROM. (2019, July 26). *International Centre for the Study of the Preservation and Restoration of Cultural Property*. International Seminar Addresses the Issue of Heritage on Fire. https://www.iccrom.org/news/international-seminar-addresses-issue-heritage-fire

ICCROM, ICOM Brazil, SBM, IBRAM, Minitério do Turismo, & Governo Federal. (2019). *Declaração do Rio de Janeiro Rio de Janeiro Declaration on Fire Risk Reduction in Cultural Heritage*.

Institute of Fire Engineers [IFE]. (2017). *Institution of Fire Engineers Special Interest Group for Heritage Buildings Fire Safety for Traditional Church Buildings of Small and Medium Size 2*. https://historicengland.org.uk/images-books/publications/fire-safety-for-traditional-church-buildings/fire-safety-traditional-church-buildings/

Iringová, A. (2020). A Case Study on the Fire Safety in Historic Buildings in Slovakia. In *Fire Safety and Management Awareness*. IntechOpen. https://doi.org/10.5772/intechopen.91241

Karlsson, B., & Quintiere, J. G. (2000). *Enclosure Fire Dynamics*. Boca Raton (Fla.): CRC Press.

Kincaid, S. (2018). The Upgrading of Fire Safety in Historic Buildings. *Historic Environment: Policy and Practice*, *9*(1), 3–20. https://doi.org/10.1080/17567505.2017.1399972

Li, J., Li, H., Zhou, B., Wang, X., & Zhang, H. (2020). Investigation and Statistical Analysis of Fire Loads of 83 Historic Buildings in Beijing. *International Journal of Architectural Heritage*, *14*(3), 471–482. https://doi.org/10.1080/15583058.2018.1550535

London Fire Brigade. (2015). *Fire Safety Guidance Note GN 80: Heritage and Buildings of Special Interest*. http://www.london-fire.gov.uk.

Luiz Pedersoli Jr, J. (2019). *Understanding the problem: Cultural heritage fire statistics*.

Manager, G., & Strudwick, B. (2015). *Surrey Fire & Rescue Service Report of Fire Fire Investigation Officer Not suitable for Civil or Criminal Proceedings Not Restricted*.

Maxwell, I. (2003). COST ACTION C17: “BUILT HERITAGE: FIRE LOSS TO HISTORIC BUILDINGS – THE CHALLENGE BEFORE US.” *CNVVF_NFPA_Conference_2003*.

Ministry for Culture and Heritage. (2018). *Heritage New Zealand Pouhere Taonga Act 2014*.

Naziris, I. A., Lagaros, N. D., & Papaioannou, K. (2016). Optimized fire protection of cultural heritage structures based on the analytic hierarchy process. *Journal of Building Engineering*, *8*, 292–304. https://doi.org/10.1016/j.jobe.2016.08.007

Pau, D., Duncan, C., & Fleischmann, C. (2019). Performance-based fire engineering design of a heritage building: McDougall house case study. *Safety*, *5*(3). https://doi.org/10.3390/safety5030045

PD 7974-5. (2014). *BSI Standards Publication Application of fire safety engineering principles to the design of buildings. Part 5, Fire and rescue service intervention (Sub system 5). :2014+A1:2020*.

PD 7974-6. (2019). *BSI Standards Publication Application of fire safety engineering principles to the design of buildings. Part 6: Human Factors: Life safety strategies - Occupant evacuation, behaviour and condition (Sub-system 6)* (BSI, Ed.).

Quapp, U., & Holschemacher, K. (2020). Heritage Protection Regulations in Germany and their Relations to Fire Safety Demands. *IOP Conference Series: Materials Science and Engineering*, *753*(4). https://doi.org/10.1088/1757-899X/753/4/042036

Shi, L., Zhang, R., Xie, Q., & Fu, L. (2009). Improving analytic hierarchy process applied to fire risk analysis of public building. *Chinese Science Bulletin*, *54*(8), 1442–1450. https://doi.org/10.1007/s11434-009-0056-z

The Guardian. (2018). *“Heartbreaking”: fire guts Glasgow School of Art for second time*. https://www.theguardian.com/uk-news/2018/jun/16/firefighters-tackle-blaze-at-glasgow-school-of-art

Torero, J. L. (2019). Fire Safety of Historical Buildings: Principles and Methodological Approach. *International Journal of Architectural Heritage*, *13*(7), 926–940. https://doi.org/10.1080/15583058.2019.1612484

UNESCO. (n.d.). *World Heritage List Statistics*. Number of World Heritage Properties by Region. Retrieved March 1, 2021, from https://whc.unesco.org/en/list/stat

Vlaamse overheid. (n.d.). *Agentschap Onroerend Erfgoed* . Over Ons. Retrieved March 7, 2021, from https://www.onroerenderfgoed.be/over-ons

Warnock, G. (2014). *Scottish Fire and Rescue Prevention and Protection: Fire Investigation Report*.

Watts, J. M. (2003). Fire-Risk Indexing: A Systemic Approach to Building-Code "Equivalency" for Historic Buildings. In *Source: APT Bulletin: The Journal of Preservation Technology* (Vol. 34, Issue 4).

Watts, J. M., & Kaplan, M. E. (2001). Fire Risk Index for Historic Buildings 1. In *Fire Technology* (Vol. 37).

Appendix A: Survey Questions