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FIRE SAFETY CONDITIONS AT HISTORIC BUILDINGS: CATHEDRAL OF PORTO CASE

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Abstract
Background: Cultural heritage consists of all assets that, being testimonies with civilization or cultural value, bearers of relevant cultural interest, should be the object of special protection and appreciation. Fire is one of the main dangers that affect cultural heritage worldwide, with an impact that can result in the total or partial loss of irreplaceable assets. **Objective**: The main objective of this text is to reflect on the implementation of protection and maintenance measures capable of preventing most fires and minimizing their effects, with a particular focus on the efforts to be made in adapting them to historic buildings, based on the case study. **Method**: The methodological design was based on documental analysis and observational and analytical study, translated into the description and analysis of the current fire safety conditions implemented in the Cathedral of Porto, proposing corrective and improvement measures, bearing the ease of their implementation. **Results/Discussion**: The elaboration of a fire safety analysis in historic buildings can be a considerable challenge and require joint action to develop minimally invasive, innovative, and sustainable solutions capable of reconciling the principles of fire safety and heritage conservation. **Conclusion**: The Cathedral of Porto only meets a few regulatory generic fire requirements.

Keywords: Fire prevention, Fire Safety, Churches, Porto Cathedral, Historic Buildings

Introduction

Under the Basic Law on Cultural Heritage (Law 107/2001, of September 8), *"Cultural heritage comprises all goods that, testimonials with civilization or cultural value and bearers of relevant cultural interest, must be the object of special protection and appreciation."* Cultural heritage is subject to various dangers that impact its continued existence and relevance. Fire represents one of the most significant threats to cultural heritage, so implementing measures capable of minimizing its effects is of the utmost importance (Kincaid, 2018; Romão & Bertolin, 2022). Historic buildings worldwide were built several decades or centuries ago without their construction considering principles of fire protection and prevention. History recorded the destruction by fire of world heritage buildings and cities such as the Library of Alexandria (48 BC), Rome (64 AD), St. Paul's Cathedral in London (1666), the Cathedral of León (1966), El Chiado de Lisboa (1988) or the Iglesia Compañía de Jesús Santiago de Chile in 1863. From 1975 to 2005, the number of disasters increased by about 400%. The annual number of affected people has nearly quadrupled, depending on the population and urbanization rise and the most recent events such as the Al-Aqsa Mosque in Jerusalem, the Notre Dame Cathedral in Paris, and the National Museum in Rio de Janeiro, Brazil. The most probable causes of fires worldwide occurred in heritage buildings from 1990 to 2019: 17% of the fires could be attributed to accidents; 21% to restoration work; 17 % to short circuits; 26 % to vandalism, and 19% to un-known cause (Venegas et al., 2021). The Cathedral of Porto, located in the city's center, constitutes a cultural and historical testimony that validates all the actions of protecting and preserving the property and all the movable heritage it incorporates. The building has a religious and heritage dating back more than eight centuries (Botelho, 2006) and occupies a prominent position in the old urban fabric of the city, which, like other old urban centers, presents an increased risk of fire, boosted by the combination of several factors, such as the probability of fire occurrence, its development, and propagation, as well as the difficulties of evacuation and combat. Recognition of risk should force the implementation of measures that improve the performance of buildings, in particular those of recognized historical and heritage value. The Cathedral of Porto, given the need to preserve its historical and secular characteristics, only meets a few of the current regulatory, generic, and prescriptive requirements, which need to consider the specificities of

historic buildings. The current prescriptive regulations and the lack of specific and robust safety policies oriented towards the protection of buildings and collections that form part of the cultural heritage support the interest in the development of this work, in the expectation that the intended descriptive and analytical approach, can con-tribute, through the presentation of solutions adapted to the context, for the improvement of the performance of the building, in terms of fire safety. It has done a short review of the scientific literature to explore state of the art on fire safety in historic buildings. Additionally, a systematic observation was carried out to analyze the fire safety conditions of the Porto Cathedral in an actual view of the Portuguese regulations. The main objective of this work is to analyze the current fire safety conditions implemented in the Cathedral of Porto, proposing, whenever justified, corrective and/or improvement measures, given the ease of implementing self-protection measures.

Materials and methods

The methodology used was established in the case study paradigm, which is essentially based on the observation and recording of evidence collected on site, preceded by a review of the scientific literature to explore state of the art, about the main challenges involving fire safety in historic buildings and the engineering solutions developed in recent years. In the systematic literature review, it was observed that the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Statement (Page et al., 2021). The search was done in the Scopus, Inspec, and Web of Science databases. In this case, the search strategy consisted of collecting all those studies whose title, abstract, or keywords contained at least one term from each of the two sets of terms considered a total of 5 possible term combinations (TC) were used as input to conduct the search, which is listed in Table 1.

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

TC - 01: “Fire Safety” OR “Fire Protection” AND “Historic Buildings”
TC - 02: “Fire Safety” OR “Fire Protection” AND “Cultural Heritage”
TC - 03: “Fire Safety” OR “Fire Protection” AND “Historic Structures”
TC - 04: “Fire Safety” OR “Fire Protection” AND “Churches”
TC - 05: “Fire Safety” OR “Fire Protection” AND “Cathedral”

The search was limited to journal articles and conference proceedings written in English between 2015 and 2022, selecting the scientific knowledge generated and constant in 24 of the 37 articles eligible for full-text reading. After analyzing the search results, a filtering process was performed to select studies relevant to the subject under consideration. Once the search and selection processes were completed, the studies were classified into different research fields according to the topics. The last phase of the methodological design consisted of systematic observation, aiming to describe and analyze the current fire safety conditions at the Porto Cathedral, obeying the order established in the Portuguese Technical Regulation on Fire Safety in Buildings.

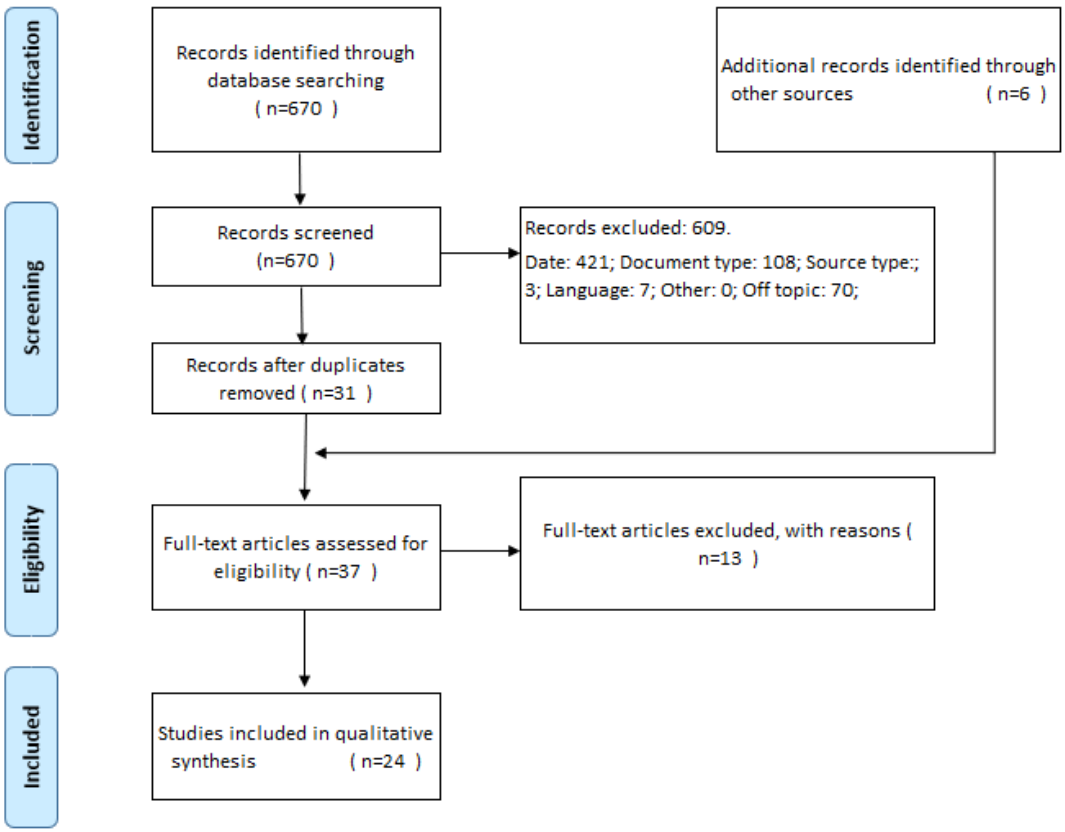

Figure 1. *Prisma Flow Diagram - methodology adopted for the literature review.*

Results and Discussion

Main considerations of the literature review on fire safety in historic buildings

Old or historic buildings are, in general, more vulnerable to fire (Torero, 2019; Raneri, 2021), which is why the most recent studies highlight the importance of investigating the vulnerability of each building, considering the context in which they are inserted and their unique needs, to understand how their structure influences the overall fire performance (Torero, 2019; Bakas et al., 2020; Salazar et al., 2021; Romão & Bertolin, 2022; Petrini et al., 2022). The bibliographic review identified some of the characteristics that make historic buildings vulnerable to fire, namely: the presence of numerous wooden structures; the absence of adequate compartmentalization; the impossibility of altering the original characteristics of the building; uncertainty regarding techniques and materials used in the original construction; the existence of voids and other elements with low fire resistance; insufficient number of alternative exits; long distances to travel, in the sense of evacuation; storage of flammable substances; non-compliance of electrical installations; difficulties in accessing emergency services and the absence of active fire detection and suppression systems (Naziris et al., 2016; Iringová & Idunk, 2017; Torero, 2019; Devi & Sharma, 2019; Kincaid, 2020; Quapp & Holschemacher, 2020; Caliendo et al., 2020; Castillo et al., 2021; Cao et al., 2021; Huang, 2022; Petrini et al., 2022). The old or historic buildings were built at a time when the principles of fire safety were not observed, presenting, for this reason, characteristics that make it challenging to apply a set of prescriptive requirements present in the current regulations. The owners and those responsible for the management of these buildings must understand that fire safety is not limited to complying with regulatory prescriptions, which aim to protect life and prevent the spread of fire to adjacent rooms or buildings, without considering the protection of their architecture and/or content (Naziris et al., 2016; Torero, 2019; Petrini et al., 2022). In general, the assessment of these buildings carried out based on prescriptions, leads to the identification of non-conformities, for which it is necessary to find equivalent and exceptional solutions, which can entail high costs (Torero, 2019; Bakas et al., 2020; Vijay et al., 2021; Kincaid, 2022; Petrini et al., 2022; Romão & Bertolin, 2022). The concern with the design of fire safety

in heritage buildings and protected structures has stimulated research to develop new methodologies, improve existing ones, and assist decision-making in the application of a more holistic view (Naziris et al., 2016; Kincaid, 2018, 2019; Bakas et al., 2020; Caliendo et al., 2020; Romão & Bertolin, 2022), which combines principles of fire safety engineering and conservative principles, which safeguard the heritage value (Kincaid, 2018; Torero, 2019; Pau, 2019; Bakas et al., 2020; Quapp & Holschemacher, 2020). The research of potential innovative solutions requires more significant investment. However, it is already possible to find in recent literature efforts to compile strategies aimed at fire safety in historic buildings (Bakas et al., 2020; Petrini, 2022). In most historic buildings, wood is a predominant building element. The fire reaction performance of wood changes over the years, with a consequent deterioration in performance and a potential decrease in fire resistance. Some methods have been developed to delay this effect, treating the wood with chemical products, namely phosphoric acid and paraffin, verifying that their application can reduce the ignition time and the heat release rate (Zhou et al., 2019). The application of mineral wool insulation to prevent the vertical spread of fire in the wooden ceiling is indicated as an alternative to the use of general solutions such as wooden boards (floor) since the flexibility of the material allows it to adapt to the movement of the structure during a fire, increasing protection (Devi & Sharma, 2019). Interventions must be carried out from the floor, not from the ceiling, especially if it is decorative, not to compromise authenticity. Likewise, when sprinklers are needed inside the roof, misted water seems to be the best option, as it avoids damage to any artwork on the ceiling (Kincaid, 2018). Several research works have addressed the use of movable smoke and fire curtains. It is claimed to be an effective alternative where partitioning with firewalls is not feasible. It can be applied to partition open stairs and be associated with a direct connection to the alarm system (Devi & Sharma, 2019). Similarly, some studies show that water mist systems can be a compartmentalization alternative, acting as a curtain (Quapp & Holschemacher, 2020; Chang et al., 2021), similar to what was done at Windsor Castle (Kincaid, 2018). Compartmentalizing elements, such as doors, can be improved by applying translucent fire-retardant material, including self-closing devices and intumescent seals (Kincaid, 2018, 2022; Torero, 2019; Yan et al., 2022).

Cathedral of Porto fire safety conditions under national regulations

The Cathedral of Porto is a building of religious worship, classified, under the terms of number 1 of article 8 of the Portuguese "Law No. 123/2019", as a use-type VI, whose risk category depends on the terms of the provisions in Annex III of that Law of the following classification factors: height, number of floors occupied below the reference plane and effective (integrated into the building and outdoors). The building is > 28 m high, has no occupied floors below the reference plane, and has an occupant load of 1100 people, thus classifying it as a fourth risk category. The building consists of three floors, with different spaces, in terms of functionality, area, personnel, and risk locations. Among other documents, Portuguese law is supported by a Technical Regulation on Fire Safety in Buildings (RT-SCIE), published by "Ordinance No. 135/2020", which is essentially organized into six large groups of fire safety measures that must be observed, both in buildings and in itinerant or temporary enclosures:

- Common external conditions, such as, for example, those related to the requirements of access roads to buildings and enclosures and accessibility to facades, among others;
- General conditions of fire behavior, insulation, and protection, which establish the conditions of fire resistance of construction elements, fire compartmentalization, insulation, and protection of risk areas and circulation routes, as well as the reaction to fire of materials used in the context of the buildings;
- General evacuation conditions, where the criteria for dimensioning evacuation routes and emergency exits are defined;
- General conditions for technical installations, which define the safety conditions to be observed in specific installations that present particular risks of fire, such as electrical installations, heating installations, ventilation, air conditioning, etc.

- General conditions for safety equipment and systems, which specify the criteria to be observed for safety signs, emergency lighting, combustible gas, fire detection, air pollution, smoke control, fire safety control room, as well as the means of fixed and portable firefighting equipment;
- General conditions of self-protection, where the definition of the organization of fire safety is found during the operation of buildings, as is the case of conservation and maintenance actions during the buildings exploration phase of the spaces and the equipment and systems, procedures and human resources to carry out firefighting, the training of these human resources and the fire drills to test and practice all these actions.

While the first five groups of those fire safety measures focus more on the design conditions and the installation of fire safety equipment and systems, the last group is related to fire safety organization during the building's usage. Additionally, there are still some specific conditions for certain use-type. The analysis of the fire safety conditions through this national regulation led to the conclusion that, in general, the building is equipped with safety means implemented to circumvent the specific and foreseeable constraints in historic buildings in an apparent attempt to reconcile the safety of the occupants and the heritage authenticity. Despite the positive evidence, some of the non-conformities were found to compromise the safety of the building, deserving, for this reason, careful reflection and intervention. In assessing the Cathedral of Porto, a predictable insufficiency is identified in the insulation and protection of the construction elements since this is a building from the 12th century when wood and stone construction predominated (Table 2).

***Table 2**. Main non-conformities at the Cathedral of Porto*

Legal requirement - RT-SCIE	**Compliance**	
	No	**Yes**
Access roads to the building		x
Accessibility to facades		x
External water supply building in case of firefighting		x
Limitations on the spread of fire outdoors		x
Availability of water for rescue facilities		x
Degree of emergency readiness		x
General fire compartmentation/partitioning	x	
Protection of horizontal and vertical escape routes	x	
Reaction to fire		x
Evacuation		x
Safety signs	x	
Emergency Lighting	x	
Detection, alarm, and warning system	x	
Smoke control system	x	
Means of firefighting equipment	x	
Safety control room	x	

On the 0th floor, the inadequate fire partitioning stands out, which is why it is suggested that three fire compartments be defined, with an area of less than 1600 m^2, whose boundaries are shown in Figure 2, on all the doors that delimit the fire compartments, from a second door or by the application of fire resistant coating systems and hardware associated, perhaps, with fire retardant agents, capable of improving fire resistance. It should be noted that in the Portuguese legislation for this type of use of buildings, there is no need to calculate the Fire Load Density, so the design of means of firefighting will depend on other aspects, such as the size of

the compartments to be protected, the type and particularity of the fire risk, etc. Risk C locations, classified as such because they have a volume> 100 m^3, are located on this floor and must be independent fire compartments.

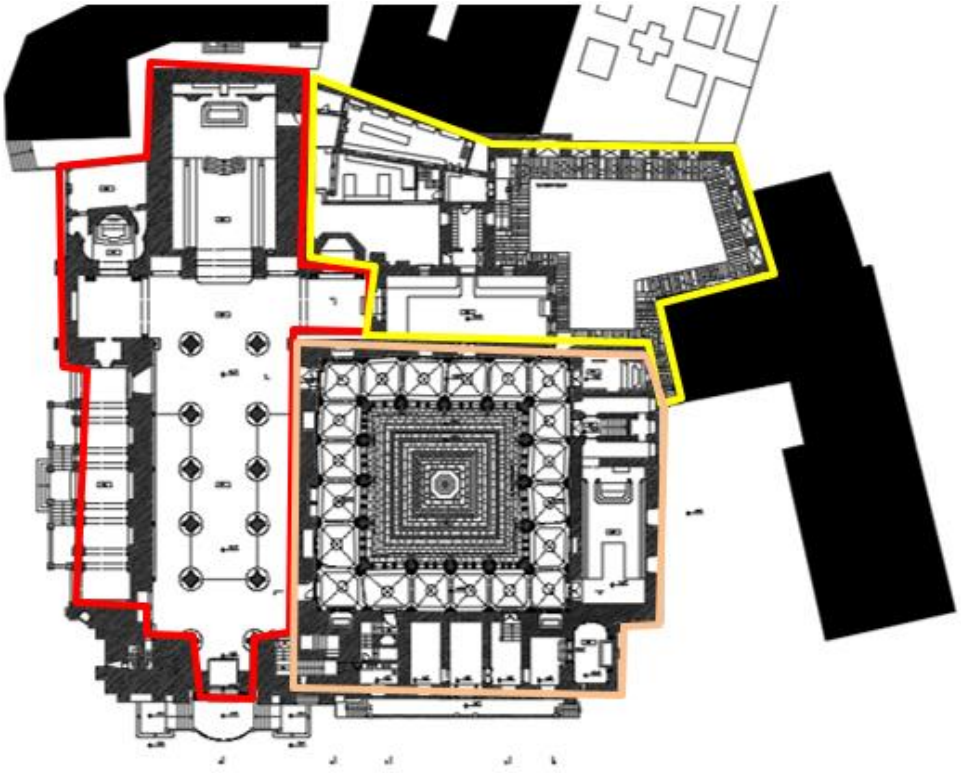

Figure 2. *Fire compartmentation of floor 0*

The area of the building where the spaces allocated to technical and administrative services are located is a more recent construction, with wooden facades, compared to the oldest part of the building (Figure 3a), so the openings in the oldest construction must be protected appropriately and ensure compartmentalization to prevent the spread of fire. On the Nasoni staircase, it is essential to reinforce the wooden side doors at the beginning of the staircase (Figure 3b) and along it to guarantee the protection of this vertical escape route from the adjacent spaces (two chapels), whose accesses can also take this ladder. On the staircase leading to the North Tower, consideration should be given to the possibility of placing a second door on the landing located at the level of the upper cloister (Figure 4) to isolate the staircase on the way down, preventing the smoke spreading to the organ area and the top of the tower, hindering its evacuation. In this way, the compartmentalization of the two areas delimited in red and brown in Figure 1 is simultaneously guaranteed.

a)  b) 

Figure 3. *a) The confrontation between the stone facade and the wooden façade; b) Wooden doors accessing the Nasoni staircase*

Figure 4. *Access to the North Tower*

In places where compartmentation with construction elements is not possible, mobile smoke, fire curtains, or water mist systems should be considered since the literature indicates this is a practical and applicable alternative, even in partitioning open stairs. Regarding evacuation, regulatory requirements are generally met, as the building has several exits that exceed needs, with widths that exceed regulatory requirements. The horizontal and vertical evacuation routes have characteristics suited to the person they serve, except the access staircase to the administrative services. In case of emergency, it is essential that the main and side doors of the church usually closed for operational reasons, are immediately opened to guarantee the occupant's safe exit to the outside. The conventional approach to emergency lighting and signage does not seem acceptable when applied to historic buildings. The need for a permanent installation is debatable, requiring an assessment considering the model for using the space. The intervention in the historic buildings, the visual impact of the installation, and the associated costs may not be justifiable. As with lighting, installing standard signage in an ornate or decorated interior may not be the best option, so signage should assume a non-standard design adapted to the interior.[1] Considering the regulatory requirements, the emergency lighting and signaling systems present significant shortcomings in the Cathedral of Porto. As a solution, the use of light-emitting diode (LED) units on the floor, which provide the emergency lighting and the placement of signs, invisible most of the time, only activated if necessary. A team trained and familiar with the internal layout of the building can be an option for directing visitors in an emergency. The limitation of the number of visitors, reflected in the reduction of the number of people to be evacuated, can be evaluated as a compensatory measure. In historic buildings, the location of fire detectors can be problematic due to the need to ensure accessibility without interfering with the structure and decoration. The smoke machine can help validate the most appropriate positioning. Some tests confirmed the reliability of wireless systems in historic buildings, highlighting the low installation cost and the fact that they are more straightforward and less invasive (Kincaid, 2018). In fire suppression, self-contained or portable water mist systems are reported as an alternative to fixed systems (sprinklers), which require more invasive and unsightly piping installations (Kincaid, 2018; Quapp & Holschemacher, 2020). In the Cathedral of Porto, the automatic detection devices, usually linear, are appropriately distributed. However, there is an insufficient distribution of alarm trigger buttons. Regarding detection and alarm, it is worth highlighting the need to ensure the integration of detection centers in a permanently monitored location, preferably at the safety control room, and ensure that the system is of the addressable type, allowing the exact location of the fire focus. Regarding smoke control, the building does not comply with regulatory requirements. The placement of active smoke extraction mechanisms in the vertical and horizontal escape routes could compromise the historic block. However, their placement should be evaluated in the technical and administrative areas. Regarding the firefighting equipment, there is a shortage of standard extinguishing agents on the 0^{th} and 2^{nd} floors when the usual dimensioning criterion is applied. It is suggested that fire extinguishers be placed in the Gothic cloister

[1] https://historicengland.org.uk/advice/technical-advice/building-services-engineering/internal-lighting-in-historic-buildings/internal-external-and-emergency-lighting/(Consulted on 08/25/2022)

and the archive room in the north wing of the church, as this is a C risk location. During the evaluation, it was found that the building does not have an established safety control room, required for a fourth category of risk, suggesting that it be implemented and located in the compartment where the current ticket office is located or in the adjoining compartment, moving the fire detection and general power cut control units to this space (Figure 5). In this way, the building will have a place that centralizes all safety information and the primary means of receiving and disseminating the alarm to be activated in an emergency. Displacement could condition circulation and force evacuation routes to be restructured.

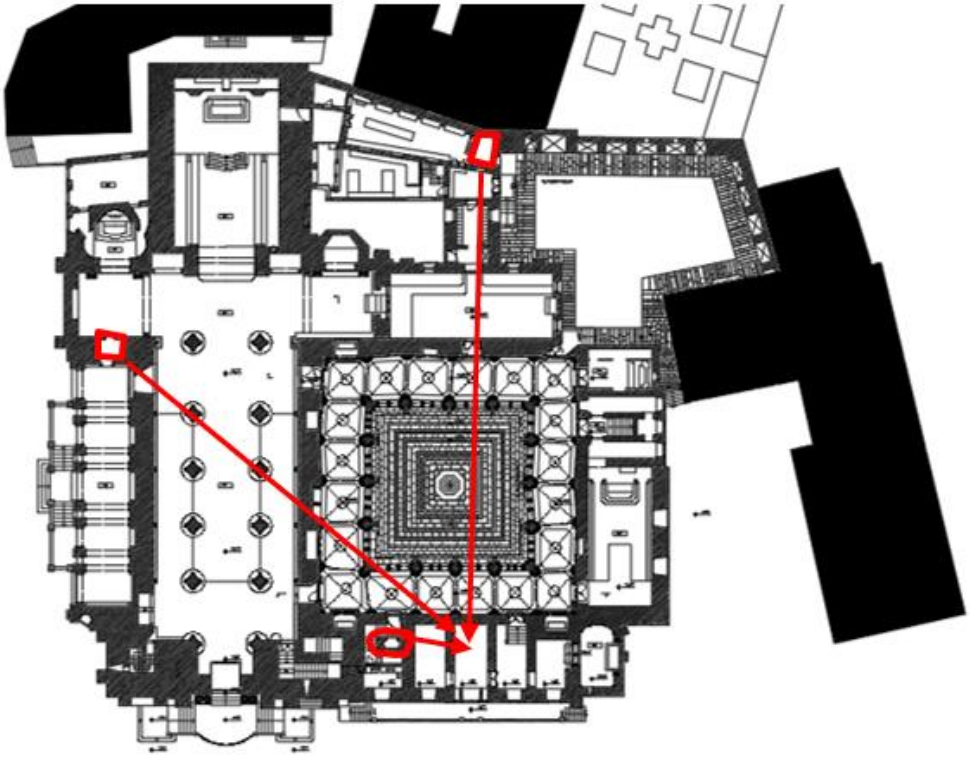

***Figure 5**. Safety Control Room*

Considering that conventional passive and active protection measures often conflict with heritage conservation principles, the literature suggests developing an integrated concept in which passive and active fire protection is combined with structural, technological, and organizational to meet the safety objectives of each building. The active cooperation of different parties interested in heritage protection should result in the presentation of viable, creative, and successful solutions aligned with the needs of communities and/or sustainability concerns (Quapp & Holschemacher, 2020; Vijay et al., 2022; Romão & Bertolin, 2022).

Conclusions

Due to its rapid spread and the devastating proportions it can reach, causing the total or almost total loss of affected property, fire is one of the greatest threats to people and property. Most fires can be avoided or reduced through procedures that prevent risk situations and the availability of means that enable detection and combat. Throughout history, there are records of fires, which, due to their devastating consequences, assumed a pedagogical role as a source of reflection and awareness of the problem, being at the genesis of the creation and development of methods and tools in the area of Fire Safety in buildings.

The bibliographic review highlighted the complex relationship between fire and historic buildings, allowing us to understand existing vulnerabilities and threats and the perspectives and challenges engineers face in designing Fire Safety in heritage structures. The conventional approach, predominant in most national and international regulations, presents solutions that do not suit the specificities of historic buildings, which is why the conviction

grows that an approach based on risk or performance will allow greater flexibility in the decision-making process. Decision-making is made, admitting the definition of objectives consistent with the specificities of the building and the development of interventions that respect and preserve the originality of the historic buildings. The critical assessment of the conditions and hazards of each building appears to be the ideal tool for fire safety strategy in historic buildings. In each case study, the different needs and constraints must be considered, as well as the basic principles for preserving the authenticity of the building, weighing the costs and benefits, and guiding the action, using up-to-date scientific knowledge, which allows compliance with the defined objectives. The developed analysis is of particular interest when reflecting on the specific characteristics of the Cathedral of Porto, concluding that the building presents several non-conformities according to current regulatory requirements, mostly related to the general fire compartmentation; the absence of complete protection of escape routes and a smoke control system; not full coverage of all spaces with the safety signs, emergency lighting, and detection and alarm system; insufficient firefighting equipment; and a safety control room to supervise the entire building. This work can boost the implementation of legally required measures in a process that considers reconciling safety and heritage conservation principles, using innovative, minimally invasive, and sustainable solutions. In a future perspective, consideration should be given to drawing up specific regulations for historic buildings, if possible, in collaboration with professionals in the area of conservation and restoration, whose knowledge will allow the establishment of more reasonable requirements adapted to the historical heritage.

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