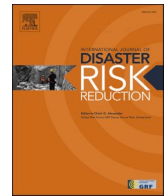


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

## International Journal of Disaster Risk Reduction

journal homepage: [www.elsevier.com/locate/ijdr](http://www.elsevier.com/locate/ijdr)

# Proposal of an innovative model for fire prevention assessment in Cultural Heritage Protection. Research study in Italy

Pasquale Cucco<sup>\*</sup>, Giacomo Di Ruocco, Luca La Rana

*Department of Civil Engineering, University of Salerno, Fisciano, Italy*

## ARTICLE INFO

### Keywords:

Fire prevention  
Life safety  
Cultural heritage  
Conservation

## ABSTRACT

The complexity of cultural heritage has often led to the belief that fire safety regulations enacted for civil constructions could be derogated due to their invasiveness in relation to the artistic peculiarities of historical assets. In many cases, the lack of effective interventions has resulted in the loss of significant historical and architectural assets, destroyed by fires over the centuries. This research aims to reconcile the regulatory parameters of fire prevention with the fundamental principles of restoration and conservation, following a performance-based approach. Building upon the Italian regulatory framework, this study develops an integrated method that adheres to both the parameters of the “Vertical Technical Rule” on historical buildings and the conservation cases associated with them. The proposed model is the result of a multiparametric evaluation based on the intersection of 3 objectives, 7 sub-objectives, and 10 strategies, defining 70 actions based on the main objective to be pursued. The methodology was applied to two case studies in Southern Italy. The results demonstrate that it is possible to ensure fire safety while preserving the unique characteristics of historical buildings through minimally invasive interventions. Furthermore, the results, which are almost identical between the two case studies, demonstrate that the methodology is applicable to each type of protected asset, including museums or galleries, buildings for exhibitions or shows, libraries, and archives, and historical churches.

## 1. Introduction

The built historical environment contains unique values that cannot be addressed by codes alone. Some of its features, such as architecture, decorations, construction techniques, etc., cannot be altered without compromising the value of the buildings. Additionally, these constructions house elements such as frescoes, paintings, artworks, religious objects, which can increase the fire load and spread potentially harmful substances (such as liquids in a natural history museum, cloths in a textile museum, wax candles in a church, etc.). These characteristics present a real challenge when it comes to adapting historical buildings to fire prevention and protection. Given the complexity of cultural heritage, managing any risk in compliance with regulatory requirements is difficult or even impossible. The devastating events that occurred at Notre Dame Cathedral in Paris (2019), Glasgow School of Art in Scotland (2014) [1], Krásna Hôrka Castle in Slovakia (2012) [2], Santa Maria della Salute Church in Venice (2010), Turin Cathedral with the nearby Royal Palace (1997), La Fenice Theater in Venice (1996), and Petruzzelli Theater (1996) demonstrate that fire safety in historical buildings has always been a major concern. Cultural heritage is particularly vulnerable to the risk of fire due to various factors, including location, materials, outdated technological systems, lack of fire compartmentation, limited active and passive protection,

<sup>\*</sup> Corresponding author.

*E-mail address:* [pcucco@unisa.it](mailto:pcucco@unisa.it) (P. Cucco).

<https://doi.org/10.1016/j.ijdr.2023.104066>

Received 23 February 2023; Received in revised form 21 September 2023; Accepted 15 October 2023

Available online 19 October 2023

2212-4209/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

and lack of training for staff. Historic buildings and environments present greater fire risk vulnerabilities compared to modern buildings. For example, longer maintenance/restoration periods, presence of wooden or similar elements/systems (furniture, curtains, paper/fabric coverings, canvases, etc.), sophisticated engineering components, restrictions on the use of fire-retardant products, architectural and artistic constraints imposed by heritage authorities, difficulties in applying common and established methodological approaches, and scenarios of interaction and interference between the construction site and daily use. The solution to fire safety for such buildings requires careful performance evaluation to explicitly demonstrate that the necessary safety objectives have been achieved. Fire safety objectives include the preservation of human life, but they must also encompass adequate protection of the heritage. Performance-based analysis allows for a design approach that values the intrinsic characteristics of historical buildings. This could potentially result in minimal and rational modifications that meet fire safety objectives while also achieving other restoration goals [3].

Italy holds a unique artistic and cultural heritage: 3500 museums, 100,000 churches, 18,500 libraries, over 20,000 castles, fortresses, and noble houses, 900 historical theatres, 1500 monasteries, and 3000 archaeological sites. Many of the buildings still in use are only partially compliant with fire safety regulations, due to the inapplicability of fire prevention parameters outlined in the general legislation (Legislative Decree No. 151/2011). The Vertical Technical Rule for fire prevention, which has been in effect in Italy since 2021, innovatively regulates fire prevention in historical buildings by delegating to the designer the decision to utilize the best solutions according to a performance-based approach. Building upon this legislation, this study aimed to develop a multitasking and integrated application methodology that respects both fire regulatory parameters and the requirements of restoration and conservation of heritage buildings, including the use of appropriate techniques and materials, sustainability, reversibility, non-invasiveness, and the preservation of all artistic and architectural elements (Fig. 1).

The paper is structured into several sections: 1. Introduction; 2. State of the Art; 3. Materials, indicating the starting reference context; 4. Methods, in which the different consequential steps are explained; 5. Description of the case studies; 6. Application of the model to the case studies; 7. Discussion and results; 8. Conclusion.

## 2. State of the art

The comprehensive review of major fire events affecting protected buildings in Italy and Europe from 1800 to the present [4] has led the scientific community to reflect on the issue of integrating fire safety and cultural heritage restoration from multiple points of inquiry. The event that struck the Basilica of San Paolo Fuori Le Mura (Rome, 1823) influenced the history of fire prevention, writing a new chapter in modern fire technology. Luigi Poletti, the engineer appointed by Pope Leo XII for the reconstruction, devised a fire protection system to safeguard the roof covering of the basilica [5]. This system, described in documents from the State Archives of Rome, relied on thermometers that, upon exceeding a certain temperature, activated the discharge of water stored in tanks located in the building’s attic. Narrowing the scope of investigation to fires in historical buildings worldwide over the past two decades (1999–2019), from a sample of approximately 90 events, recent research [6] shows that the top five causes of fire ignition were: vandalism (26 %), neglect and negligence in restoration sites (21 %), electrical problems and short circuits (17 %), accidents (17 %), and unknown causes (19 %).

[7] conducted a study on the effects of fire on decorative stucco elements, including mouldings and painted decorations, in the Petruzzelli Theatre in Bari, Italy. In 1991, a fire caused severe damage to both the materials and the structure of the theatre. The effects of the fire on the surface were carefully examined in a laboratory setting, focusing on mineralogical, chemical, and microstructural

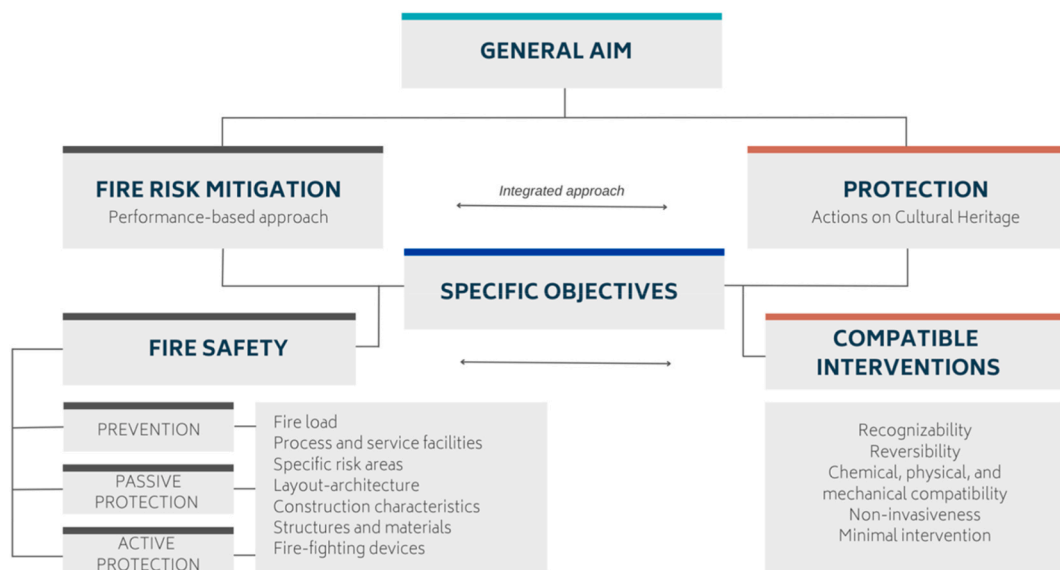


Fig. 1. General Aim and specific objectives of the research.

alterations. [8] focused on the design of low-impact interventions aimed at increasing the safety level for occupants while preserving the original characteristics of the heritage. These solutions are based on a “behavioural design” approach, proposing non-invasive solutions for the safety of occupants in historical buildings, where they are truly necessary, considering their effects on users. Investigations were carried out on human-environment interactions during evacuation. It is possible to design building components that are easy to apply and interact with users during evacuation without introducing any architectural modifications to the layout and original features of the building.

Following the Notre-Dame fire in 2019 in Paris, [9] highlight that, although the immediate effects of the event did not cause any casualties, the technological characteristics of the installation led to the volatilization of a significant amount of lead particles deposited in the surrounding areas, posing a real risk of intoxication for residents. Then, [10] have used the French event as a validation case for improving fire safety modelling in historic buildings. Referring to the fire at Krásna Hôrka Castle in 2012, [2] focuses on the issue of fire safety in historical buildings undergoing functional modifications, restoration work, facade element renewal, or installation component renovation.

[1] analyses the 3D digital emergency documentation program in areas affected by the fire that devastated the Glasgow School of Art in 2014. The research highlights the benefits of 3D digital representation for disaster management and emergency decision-making. The documentation results produced an accurate, high-resolution 3D spatial record of a significant historical building, despite the alterations to the material properties of the post-fire interior environment. Data analysis provided conservation and building control teams with significant parameters for building access, health and safety, and structural deformation.

[11] analyses the challenges related to fire safety in historical buildings, including modelling the human factor and the human-environment-fire interaction in these architectural spaces. The study proposes low-impact and non-invasive strategies, such as those based on wayfinding elements. In recent years, the need to improve the indoor comfort of historical buildings, particularly regarding energy standards and reducing carbon footprint, has required significant technological and structural interventions carried out by operators with limited or no knowledge of fire prevention. As a result, these heritage buildings lack the necessary equipment in the event of a fire and are often subject to inadequate interventions, leading to severe incidents.

[12] emphasizes that a specific fire risk assessment for heritage, beyond legislative regulations, should be the starting point for all preventive actions. Even when such risk assessments are not required by fire safety regulations (e.g., in private residences) or stipulated as insurance conditions, they are an essential tool for systematically examining all aspects of fire risk.

[13] emphasize that risk perception influences regulations. Revealed preference theory is useful for developing quantifiable methods to incorporate risk perception into a performance-based building fire safety code. The authors define two methods that outline different ways in which risk perception can be integrated into a performance-based building fire safety code.

BS 9999:2017 [14] is the fire safety code of practice for the design, management, and use of buildings. It is based on government guidelines and provides a framework of best practices for fire safety. The standard outlines ways to test all aspects of the fire strategy, including easy access to exits, to ensure the safety of people inside and around buildings. This includes how to manage fire safety throughout the entire lifecycle of the building, from design or redesign to assessing the fire detection system and maintaining a fire detection system.

[15] highlights that, compared to traditional prescriptive fire regulations, the performance-based approach offers a wide range of advantages, such as flexibility in choosing the most appropriate design solution, thanks to a more realistic definition of fire scenarios. In contrast, performance-based design requires greater expertise and knowledge in this field, especially when numerical fire or evacuation models are required. In this case, the designer’s sensitivity can strongly influence the results and thus the proposed solution.

[16] propose a series of vulnerability indicators for assessing fire risk in cultural heritage assets. The study defines, among other things, a classification of cultural heritage assets into four classes (1: archaeological sites, 2: compartmentalized buildings, 3: historic centres, 4: isolated monuments) focusing on their vulnerability to fire and discussing the applicability of the proposed Fire Vulnerability Indicators (FVI) to these classes. Since there is still a need for a fire risk assessment method that comprehensively and flexibly addresses the safeguarding of cultural heritage assets and their values, the proposed FVI is suggested as a basis for the development of future methods.

### 3. Materials

#### 3.1. Starting data

The Italian Ministerial Decree of August 03, 2015, known as the “New Fire Prevention Code” represents a significant milestone in fire prevention activities in Italy. It transitions from prescriptive methods to performance-based methods, allowing for a better expression of the capabilities and professionalism of designers, making the regulatory framework more aligned with technological advancements and international standards. The product is a “horizontal technical regulation”, which constitutes a true code of principles and modern fire prevention techniques, complemented by specific “vertical technical rules” for individual activities. The purpose of this text is to provide guidance for a better understanding of the regulatory framework and fundamental principles in the field of fire safety [17].

In general, there are three existing fire safety approaches. The prescriptive approach, comprised of various ministerial decrees, is regarded as a guideline that the designer can refer to in order to achieve the minimum required level of safety. The semi-prescriptive approach of the Fire Prevention Code, specifically the ministerial decree of August 3, 2015, which serves as a comprehensive manual for professionals as it contains both the horizontal technical regulation and all vertical technical rules.

Finally, the performance-based approach of Fire Engineering, which, unlike the other approaches, allows the designer more

independence in their choices, utilizing simulations to recreate a possible fire scenario and studying the minimum performance requirements of the structure in case of an emergency [18].

### 3.1.1. “Technical fire prevention standards for listed buildings” (Italian ministerial decree October 14, 2021)

In Italy, fire prevention regulations prescribe the requirements for various activities in publicly accessible and historic protected buildings. The conservation needs often hinder compliance with the requirements imposed by a deterministic approach. In many cases, adaptation is difficult, if not impossible. Since 2021, Italy has implemented the Vertical Technical Rule (RTV) for fire prevention in protected buildings, in accordance with Italian Legislative Decree No. 42/2004, which allows the designer to propose alternative solutions based on the specific features of the historical building. The currently applicable RTVs for protected buildings in Italy are: RTV 10 protected property, museum or gallery, buildings for exhibitions or shows, library, archive, protected asset storage; RTV 12 protected building and damage limitation plan. The RTV includes the following provisions:

3.1.1.1. *Classifications.* TA: areas open to the public dedicated to exhibition halls, TC: areas not open to the public used for offices and services, with a surface area  $>200\text{ m}^2$ , TM: storage areas with a gross area  $>25\text{ m}^2$  and specific fire load  $q_f > 600\text{ MJ/m}^2$ , TK1: areas where hazardous substances or mixtures are stored or handled, or hazardous processes are carried out; areas with a specific fire load  $q_f > 1200\text{ MJ/m}^2$  (e.g., restoration laboratories, workshops, carpentry workshops, etc.), TK2: storage of protected assets, TO: areas with occupancy  $>100$  people (e.g., conference rooms, classrooms, etc.), TT: areas where significant quantities of electrical and electronic equipment are present (e.g., data processing centres, server rooms, electrical cabinets, etc.), TZ: other areas not included in the previous categories (e.g., underground areas, towers, attics, etc.).

3.1.1.2. *Reaction to fire.* For vertical escape routes, escape paths (e.g., corridors, atriums, filters, etc.), and calm spaces, materials belonging to at least fire reaction group GM2 must be used. Verification of fire reaction requirements is not required for protected assets, including historical furnishings (bookcases, cabinets, curtains, armchairs, furniture).

3.1.1.3. *Fire resistance class.* For TA, TC, TO areas where the nature of the protected asset makes it impossible to adapt or determine the required fire resistance class, the following additional requirement must be met:  $q_{f,d}$  value (Value of the specific fire load of the project)  $< 200\text{ MJ/m}^2$ , calculated excluding combustible load-bearing structural elements and protected assets.

3.1.1.4. *Compartmentation.* TA and TO areas must not be located at an elevation  $< -5\text{ m}$ . The activity areas must have the required compartmentation characteristics.

3.1.1.5. *Compliant solutions for evacuation.* Along evacuation routes, doors that are not easily identifiable and operable by all occupants are allowed, provided they are kept constantly open during the operation of the activity.

3.1.1.6. *Damage limitation plan.* It is a document that contains measures and procedures for safeguarding the building and the protected assets within it in case of fire. The plan must identify the appropriately trained individuals responsible for implementing the procedures contained in it, the qualitative and quantitative distribution of the protected assets present, the procedures for removing the assets, detailing, where possible, the evacuation priorities and specific measures for their removal and transportation to shelter locations, the potential shelter locations for removed assets in case of emergency, with particular reference to the safety and preservation conditions of the assets, the procedures for on-site protection of immovable or difficult-to-move assets, any restrictions on the use of extinguishing substances.

## 4. Methods

This research is developed within the performance-based approach, as it allows an approach to fire design that enhances the intrinsic characteristics of historic buildings while preserving their value. Such a methodology aims to govern the process of interventions on historic buildings through minimal and rational modifications that meet fire safety objectives while also achieving other restoration goals [3]. In the case of historical buildings, a prescriptive approach may lead to unfeasible solutions. Therefore, a performance-based approach, focused on achieving a specific performance rather than mere compliance with a prescription, is more suitable. This allows the designer to study specific and targeted solutions to achieve the desired performance while considering all related risks. In principle, the performance-based approach ensures results that are more tailored to the specific case examined. This research aims to combine prescriptive regulations with a performance-based approach, respecting the preservation requirements of historical buildings.

The methodology developed in this research consists of the following phases:

- 1st phase: State-of-the-art analysis, to extract significant data in terms of ignition causes and types of fire load.
- 2nd phase: Development of the fire performance evaluation model, characterized by the intersection of objectives and strategies determined following phase 1, and definition of the corresponding threshold parameters (MOD\_A).
- 3rd phase: Evaluation of technical intervention solutions.
- 4th phase: Development of the compatibility assessment model for interventions with restoration requirements, and definition of the corresponding threshold parameters (MOD\_B).

### 4.1. State-of-the-art analysis

The first step for a correct approach to the subject is to learn about past events in historic buildings, investigating the environmental, social, and architectural conditions, as well as the causes that led to the disastrous event. By analyzing the state of the art and the most significant fires throughout history, two diagrams have been developed in Fig. 2. They depict the most common causes of ignition and fire spread, as well as the key parameters involved.

#### 4.2. Fire approach (MOD\_A)

The developed model combines the objective of fire retrofitting with possible intervention strategies. Each intervention strategy corresponds to potential corrective actions that can be implemented on a case-by-case basis, depending on the unique characteristics of the historical building. The main criteria for defining intervention techniques are high performance (based on the strategic objective), use of eco-friendly products (free from toxic substances that could have harmful effects in case of fire), and lower intervention costs. The methodological framework, illustrated in Table 1, refers to fire safety measures defined by horizontal technical regulations (to be evaluated based on specific compliance with the Vertical Technical Regulation), while preventive and protective measures are relied upon for fire safety objectives to be pursued.

The matrix in Table 1 defines the baseline framework (objectives/strategies) that must necessarily be met in case of fire retrofit. This baseline profile contains the minimum actions to meet the Italian regulations, with reference to fire retrofit interventions on historic buildings.

The intersection of objectives and strategies defines the actions to be implemented through *n* technical solutions, divided into (a) standard and (b) specific solutions, which the planner can adopt, on a case-by-case basis, depending on the characteristics of the asset to be protected (Table 2).

Where:

GM0: group of materials consisting of all materials having Italian fire reaction class 0 or European fire reaction class A1. These materials are also referred to as non-combustible materials. GM1: group of materials consisting of all materials corresponding to performance level "IV": materials that make a limited contribution to the fire. SVOF: horizontal forced smoke and heat ventilation systems.

SEFC: systems for smoke and heat evacuation.

#### 4.3. Evaluation of technical intervention solutions

##### 4.3.1. Criteria for defining technical solutions

For the definition of possible technical intervention solutions, numerous professionals in the field of architecture and cultural heritage (architects, engineers, economic operators, professionals specialized in fire prevention, restoration of cultural heritage, etc.) were consulted. A sample of 120 valid responses was obtained through the administration of a questionnaire structured as follows:

- Indication of at least three alternative techniques applicable to the case studies.
- The indicated techniques must consider the following priority criteria: satisfaction of the strategic objective, eco-compatibility, intervention cost (better eco-compatibility meets the need to design a sustainable intervention to achieve favourable scores in the contract award process; a lower product and intervention price helps control costly budget overruns, which often characterize interventions on historical buildings).
- The indicated techniques must satisfy restoration requirements in terms of recognizability, reversibility, compatibility, minimum intervention, and non-invasiveness.

Questionnaires were administered to approximately 200 individuals. These individuals were categorized into the following professional groups:

- Experts in fire design with over 10 years of professional experience in the field (incidence relative to the total number of respondents = 30 %).

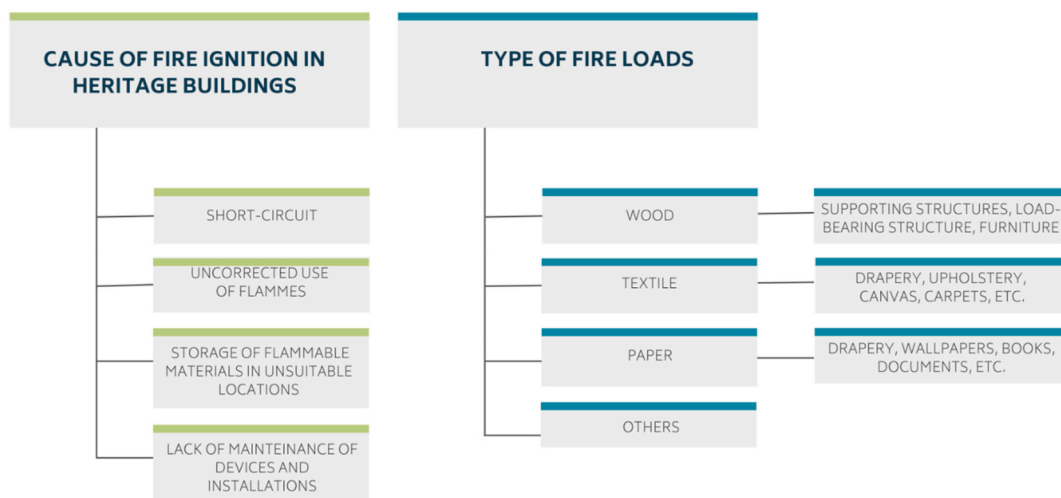


Fig. 2. Main causes of fire ignition and types of fire load.

**Table 1**  
Methodological outline (MOD\_A).

			STRATEGIES									
			Fire reaction	Fire resistance	Compartmentation	Exodus	Fire safety management	Fire control	Detection and alarm	Smoke and heat control	Fire operation	Safety of technological and service facilities
<b>OBJECTIVES</b>	<b>Prevention</b>	Fire loads	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
		Process and service facilities	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10
		Specific risk areas	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10
	<b>Passive protection</b>	Architecture layout	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10
		Construction features	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	5.10
		Structures and materials	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	6.10
	<b>Active protection</b>	Firefighting equipment	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	7.10

- Experts in restoration of cultural heritage with over 10 years of professional experience in the field (incidence relative to the total number of respondents = 30 %).
- Experts in historic building safety management with over 10 years of professional experience in the field (incidence relative to the total number of respondents = 20 %).
- Economic operators selected with over 10 years of experience in the field (incidence relative to the total number of respondents = 20 %).

Valid responses received totalised 120. The questionnaires were structured using the pairwise comparison method with the Analytic Hierarchy Process (AHP). The results were determined by taking the arithmetic mean of the partial results obtained for each of the evaluation criteria.

#### 4.3.2. Evaluation of technical solutions

Below are some of the possible technical intervention strategies according to product type, cost, and eco-sustainability. Each intervention must be compared with the principles of restoration and the typological, technological, and figurative characteristics of historic properties.

In most historical buildings, there is a significant number of wooden elements that need to be appropriately treated to improve their resistance and reaction to fire. Since the application of intumescent paints on visible elements would cause aesthetic damage due to swelling, the alternative solution to achieve the required fire reaction class is based on the application of transparent fire-retardant varnishes.

For non-exposed structural parts, steel, or concrete, to increase the fire resistance and reaction to fire, an evaluation can be made among the most popular intumescent products.

In general, historical buildings are often characterized by large compartments that need to be reduced through strictly fire-resistant firewalls. The choice falls on gypsum fibre panels, fixed on metal studs with the interposition of mineral wool. This solution can also be applied for suspended ceilings, cladding of steel or concrete elements, and the creation of technical volumes for the passage of installations.

For the selection of closure systems, door, and window frames, it is necessary for them to have predetermined fire resistance classes (REI) based on the specific environments, dimensions that ensure a quick and safe evacuation, and to be equipped with self-closing devices and panic bars. Since restoration criteria must also be considered, a deep comparison must be conducted among different products, using those with an REI 60 class as a reference.

For escape routes, a limited invasive approach is aimed by adapting vertical escape paths, corridors, atriums, filters, and existing calm spaces, both in terms of geometry and material use. Vertical escape paths, when possible, should be protected by enclosing them with perimeter fire-resistant walls, installing self-closing doors in openings, along with appropriate emergency lighting systems and ventilation openings. This choice is preferred over the construction of internal smoke-proof staircases, which are more costly to implement and technically challenging to incorporate into a historical building. Alternatively, the design of prefabricated external staircases with a metal structure can be considered, which, although invasive, meet the requirements of reversibility and recognition compared to the original building.

Regarding corridors, atriums, and filters, it is necessary to remove any potential obstacles to occupant evacuation and simplify paths to reach the exterior of the building or properly marked safe areas. The installation of emergency lighting systems for escape routes, panic areas, and high-risk areas must also be provided.

The fire control strategy varies depending on the contents of the building; for activities such as museums, galleries, exhibitions, libraries, and archives, it is advisable to use extinguishing products compatible with the protected assets present. Excluding water and foams as highly damaging in case of activation, the possible compatible products have been identified in according to cost, eco-friendly

**Table 2**  
Potential technical interventions.

Technical interventions	
1.1: suitable protection of combustible materials	SPECIFIC
1.2: compatible fire-retardant treatments	SPECIFIC
1.3: subdivision of areas with non-invasive structures	SPECIFIC
1.4: materials belonging to the GM0 or GM1 group	STANDARD
1.5: storage of materials in suitable places	STANDARD
1.6: suitable sizing of fire-fighting equipment	STANDARD
1.7: monitoring high fire load areas	STANDARD
1.8: verification of opening sizing for high fire load areas	STANDARD
1.9: accessibility of areas with high fire load	STANDARD
1.10: suitable arrangement of facilities in areas with high fire loads	SPECIFIC
2.1: suitable insulation and plant protection	SPECIFIC
2.2: pipe insulation	SPECIFIC
2.3: closing crossings with suitable elements	SPECIFIC
2.4: systems on separate networks	SPECIFIC
2.5: connection and interaction between facilities	SPECIFIC
2.6: extinguishing aid systems	SPECIFIC
2.7: plant automation	SPECIFIC
2.8: disposal and ventilation systems	SPECIFIC
2.9: location of facilities in easily accessible areas	STANDARD
2.10: suitable refrigerant gases	SPECIFIC
3.1: suitable protection flammable materials	SPECIFIC
3.2: flammable materials storage limit	SPECIFIC
3.3: reducing the size of compartments	STANDARD
3.4: forced ventilation systems	SPECIFIC
3.5: training of the personnel in charge	STANDARD
3.6: evaluation of plant type	SPECIFIC
3.7: correct placement of devices	STANDARD
3.8: suitable availability of protective equipment and devices	SPECIFIC
3.9: ready availability of extinguishing agents	STANDARD
3.10: power supply network of high-risk areas separated from the ordinary one	STANDARD
4.1: removal of materials from escape routes	STANDARD
4.2: compartments distinguished by homogeneous risk characteristics	STANDARD
4.3: firewalls	SPECIFIC
4.4: sizing of escape routes according to users	STANDARD
4.5: identification of shelter locations	STANDARD
4.6: accessibility of vulnerable areas	SPECIFIC
4.7: Correct placement of detection and alarm systems	SPECIFIC
4.8: Uniform arrangement of disposal openings	SPECIFIC
4.9: Ensure the accessibility of emergency vehicles	STANDARD
4.10: Plants derived from the primary distribution network	STANDARD
5.1: compliance with safety distances	STANDARD
5.2: materials of a suitable strength class	STANDARD
5.3: compatibility with the character of the heritage building	STANDARD
5.4: adaptation of escape routes	SPECIFIC
5.5: appropriate organization and division of spaces	STANDARD
5.6: reduction of obstacles to control action	SPECIFIC
5.7: installation of sensors on elements without historical-artistic value	STANDARD
5.8: avoid interference of openings with other environments	STANDARD
5.9: removal of elements hindering fire-fighting operations	STANDARD
5.10: protection against electric shock	STANDARD
6.1: fireproof materials	SPECIFIC
6.2: regular maintenance actions	SPECIFIC
6.3: suitable materials	STANDARD
6.4: materials belonging to the GM0 or GM1 group	STANDARD
6.5: fireproof materials	STANDARD
6.6: extinguishing agents in relation to content	SPECIFIC
6.7: adaptation of any existing systems of the structure	STANDARD
6.8: suitable materials for openings	SPECIFIC
6.9: escape stairs for evacuation from upper floors	SPECIFIC
6.10: earthing system connected to possible conductor elements	STANDARD
7.1: correct installation of fire-fighting equipment	STANDARD
7.2: compatible fire-fighting equipment	STANDARD
7.3: correct sizing of fire-fighting equipment, for each compartment	STANDARD
7.4: automatic and manual shutdown system	SPECIFIC
7.5: restrictions on the use of extinguishing substances	SPECIFIC
7.6: Adaptation of equipment according to types of extinguishing agents	SPECIFIC
7.7: mutual connection of any installations	SPECIFIC
7.8: mutual connection between the headmasters and the SVOF and SEFC systems	SPECIFIC
7.9: dry columns	SPECIFIC
7.10: elimination of possible conflicts.	STANDARD

and compatibility with historic values.

Regarding the installation of detection and alarm systems, it has been assessed that the components of traditional systems often require a significant amount of wiring; therefore, the use of IRAI systems (fire detection and alarm systems) in accordance with the EN 54-25 standard is proposed. Cost and eco-friendly features do not differ greatly among the various companies on the market. For surveillance of environments with a height of more than 6 m, linear smoke detectors can be used (EN 54-12 - Linear beam detectors), which through infrared technology are also suitable for the surveillance of domes, adopting a diagonal installation.

For smoke and heat disposal, depending on the performance level, the suitability of the size and distribution of disposal openings should be verified; if the verification is not met, provide a horizontal forced ventilation (SVOF) and smoke and heat evacuation (SEFC) system. Compatible and unobtrusive devices for automatic opening of doors and windows in case of emergency can also be installed, thus enabling smoke evacuation and ventilation depending on the configuration.

About plant engineering, it must be ensured that the emergency power supply circuit is separate from the ordinary power supply circuit; it must also be provided with self-powering and made in accordance with the provisions of CEI 64-8 standards. The protection of gas networks and electrical installations must be done with insulating products such that they are protected during the development of flames and high temperatures.

Next, satisfaction thresholds were defined as follow (Table 3):

- 0 to 5 valid intervention strategies → the model is not satisfied.
- from 6 to 10 valid intervention strategies → the model is satisfied.

The minimum threshold was determined by the criterion of an absolute majority of satisfied strategies, defined by the formula:  $T_{min} = [50 \% * 10 + 1]$ .

This model was tested according to three parameters: intervention not met by the state of the art; feasible intervention; unfeasible intervention (Table 4).

Following the application of the model to the case studies, a matrix relating to the situation will be obtained for each of them, as well as a post-intervention matrix where any improvements obtained will be evaluated, demonstrating the effectiveness of the method.

#### 4.4. Restoration approach (MOD\_B)

Architectural restoration intervention should be designed at least in accordance with the following specific goals: recognizability, reversibility, compatibility, minimal intervention, and interdisciplinarity. *Recognizability*: any restoration intervention must be recognizable, so any part added must be distinguishable from the original, without altering the good. *Reversibility*: any restoration work must be able to be removed without damaging the original pre-existence. *Compatibility*: the materials used must not cause physical or aesthetic damage to the original materials, so they must have the same chemical-physical-mechanical properties. *Minimal Intervention/Non-invasiveness*: restoration intervention limited to the minimum, to avoid any form of potential the stress.

Finally, a matrix aims to identify the possible interventions that are compatible with the above-mentioned principles (Table 5).

Table 6 shows the impact of each of the strategies, used in the model’s development on the main criteria, with a range of values between 86 % and 100 %. Overall, the model is 93.8 % compatible with restoration principles (pre-intervention scenario). This percentage defines the value-threshold of the restoration compatibility factor (Fcr).

Therefore, to ensure the effectiveness of the intervention in accordance with the restoration criteria, the following threshold value was determined.

$$F_{cr} > 93,8 \%$$

The value of 93.8% is the theoretical minimum threshold for the application of the model to achieve the set goals.

### 5. Description of case studies

The buildings considered for the case studies refer to the second type of cultural heritage assets highlighted in Salazar et al.’s study (2021), namely “compartmentalized buildings”. The analysed cases share the same characteristics in terms of crowd flows, access dynamics, and egress patterns.

These buildings are located both in Salerno, Southern Italy: Church of St. Benedetto and the Provincial Archaeological Museum, both of which are part of the ancient monastic complex of San Benedetto (Fig. 3). The buildings are located within the city’s historic centre, in an urban context that presents multiple criticalities from the point of view of fire prevention: narrow streets, often one-way streets, reduced accessibility, and lack of adequate manoeuvring and emergency vehicle spaces.

**Table 3**  
Definition of thresholds for meeting fire prevention compliance.

	STATEGIES										Threshold level (n)	Strategies carried out (n)	Check	
OBJECTIVES	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI
	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	TI = 6	Sc (1 + 10)	Sc > TI

**Table 4**  
Application of the model to a typical scenario, in relation to the possible scenarios.

STATEGIES										Threshold level (n)	Strategies carried out (n)	Check	
OBJECTIVES											6	1	Unsatisfied
											6	1	Unsatisfied
											6	1	Unsatisfied
											6	5	Unsatisfied
											6	5	Unsatisfied
											6	1	Unsatisfied
											6	0	Unsatisfied
Unsatisfied interventions in the state of the art													
Feasible adaptation measures													
Unfeasible upgrades													

**Table 5**  
Model for assessing the compatibility of the intervention with respect to restoration instances (MOD.B).

		RESTORATION AND CONSERVATION CRITERIA				
		Recognizability	Reversibility	Compatibility	Non-invasiveness	Average satisfaction
STRATEGIES	Fire reaction	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Fire resistance	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Compartmentation	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Exodus	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Fire safety management	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Fire control	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Detection and alarm	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Smoke and heat control	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Fire operation	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
	Safety of technological and service facilities	(1+7) / 7	(1+7) / 7	(1+7) / 7	(1+7) / 7	0% + 100%
<b>Compatibility Factor with the Restoration and Conservation Criteria</b>						0% + 100%

**Table 6**  
Typical application of the model to a typical state of the art.

BASELINE MODEL		RESTORATION AND CONSERVATION CRITERIA				
		Recognizability	Reversibility	Compatibility	Non-invasiveness	Average satisfaction
STRATEGIES	Fire reaction	7/7	3/7	7/7	7/7	86%
	Fire resistance	7/7	3/7	7/7	7/7	86%
	Compartmentation	7/7	7/7	7/7	4/7	89%
	Exodus	7/7	7/7	7/7	7/7	100%
	Fire safety management	7/7	7/7	7/7	6/7	96%
	Fire control	5/7	6/7	7/7	6/7	96%
	Detection and alarm	7/7	7/7	7/7	7/7	100%
	Smoke and heat control	7/7	7/7	7/7	5/7	93%
	Fire operation	7/7	7/7	7/7	6/7	96%
	Safety of technological and service facilities	7/7	6/7	7/7	7/7	96%
<b>Compatibility Factor with the Restoration and Conservation Criteria</b>						93,8%

5.1. Study case 1: Church of St. Benedetto

The St. Benedetto Church was built in the late 700s AD. The interior is divided into three naves by columns and pillars connected by round arches. The nave ends in a wide semi-circular apse, and an 18th-century Baroque chapel can be found at the northern end of the left aisle [19]. The main façade is distinguished by a three-arched pronaos on bare columns and the remains of the ancient bell tower. The church had a long evolutionary history, under various uses (Fig. 4). In 1811, when worship ceased, it was used as a theatre. It was redesigned for liturgical use in 1845 and served as a military district depot until 1868. In 1963 it has been redesignated as a church, and in 1969 restoration work began [20] (Fig. 5).

Based on direct site surveys, possible combustible materials and fire vulnerabilities of the building were identified, as showed in Table 7.

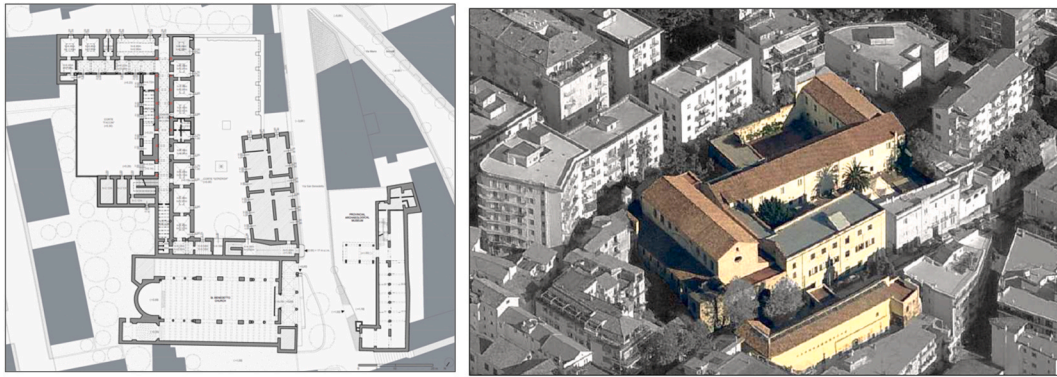


Fig. 3. Plan and 3D satellite view of St. Benedict Monastery in Salerno with the identification of the Church and the Provincial Archaeological Museum.

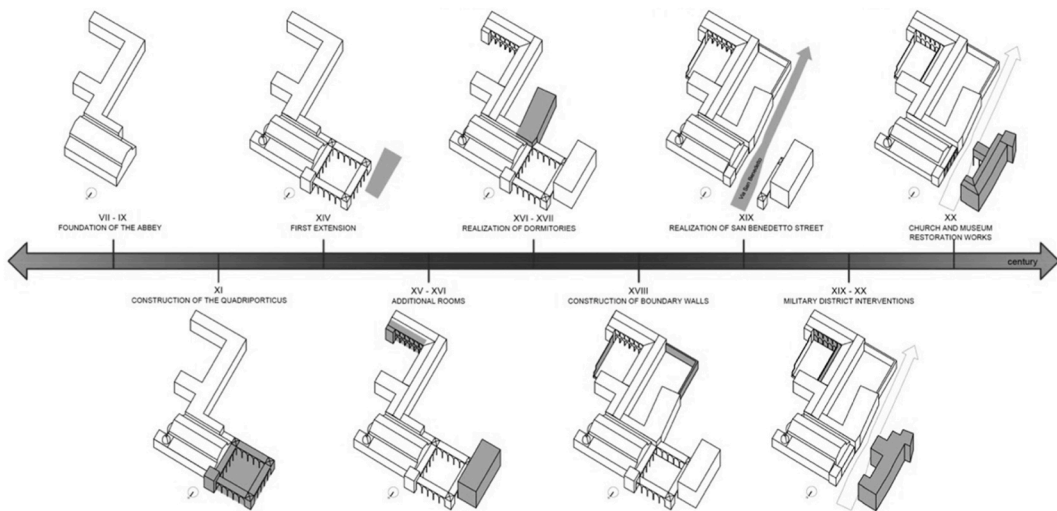


Fig. 4. Historical evolution of the San Benedetto Monastery in Salerno, Italy.



Fig. 5. Current state of St. Benedict's Church.

The technical solutions comply with the criteria for the preservation of historic buildings, in accordance also with the objectives of economy and environmental friendliness. For wooden materials, the application of fire-retardant paint RU 0010, with catalyst RZ 0020 in the ratio 1/5, put in place at a temperature of not less than 10 °C, is planned. For non-valuable fabrics, it is planned to replace them with flame retardant ones, while for the canvases placed along the aisle, it is planned to move them to more suitable environments. Regarding access, automation of the entrance window is planned. Non-slip strips and a security night lighting system will be installed on the external access steps. This system will also have to extend into the interior of the building, separate from the ordinary lighting system. An automatic aerosol fire-fighting system with potassium salts, by Green Safety, is planned, which guarantees non-invasive intervention; each fire-fighting generator is equipped with an electric-type actuator that, upon contact with the solid extinguishing

**Table 7**

Fire vulnerability of St. Benedict's Church.

CASE 1: CRITICALITY AND VULNERABILITY TO FIRE
Wooden elements: nave truss, altar stage, baroque chapel stage, cladding of entrance structure, furniture elements (pews, chairs, confessional, lecterns)
Paintings and textiles: paintings along the nave, altar and confessional textiles
Inadequacy of escape routes and presence of obstacles along them
Reduced aeration of the space
Absence of security lighting system
Absence of automatic and manual fire-fighting system
Absence of the detection and alarm system
Presence of potentially dangerous triggers
Limited space in front and not easy access for emergency vehicles

product, triggers the chemical reaction with the release of the agent in the form of an aerosol. Regarding the detection system, it is planned to install linear smoke sensors so that the trusses, semi-circular apse and side chapels can also be monitored. The gas-fired mushroom stoves will be removed, and only the existing convector heaters will be used for space heating. The existing public address system with automated sending of recorded voice messages and their specification will have to be adapted and used for signalling. Outside, an above-ground fire hydrant is to be installed.

### 5.2. Study case 2: Provincial Archaeological Museum

The Provincial Archaeological Museum was planned in 1867, but its current construction dates to 1927, within the Monastery complex of St. Benedetto.

The interior consists of a large, highly articulated room, in which the old structures alternate with the new inserts, designed for both static and exhibition purposes, after restoration in the 1960s [21,22] (Figs. 6 and 7).

Based on direct site surveys, possible combustible materials and fire vulnerabilities of the building were identified, as showed in Table 8.

Wooden elements (vitrines, furniture, walkways, steps, panelling, etc.) will be treated with fire retardant paint RU 0010. Because of their non-historical-artistic value, the didactic and representational canvases along the route will be replaced with prints on fire retardant media. The glass access door with automatic opening will be connected to the emergency electrical system. In terms of environmental ventilation, to avoid the installation of invasive ventilation systems, a portion of the continuous glass window will be equipped with automated opening in the event of an alarm. The emergency electrical system will be distinct from the ordinary one. All off-track wiring of the electrical network will be protected with fireproof KBS COATING paint; crossings near the offices adjacent to the staircase and vertical crossings between the ground and second floors will be sealed with KBS MORTAR. Existing fire extinguishers will be used for manual fire extinguishing, while aerosol generators with potassium salts from Green Safety will be installed for the

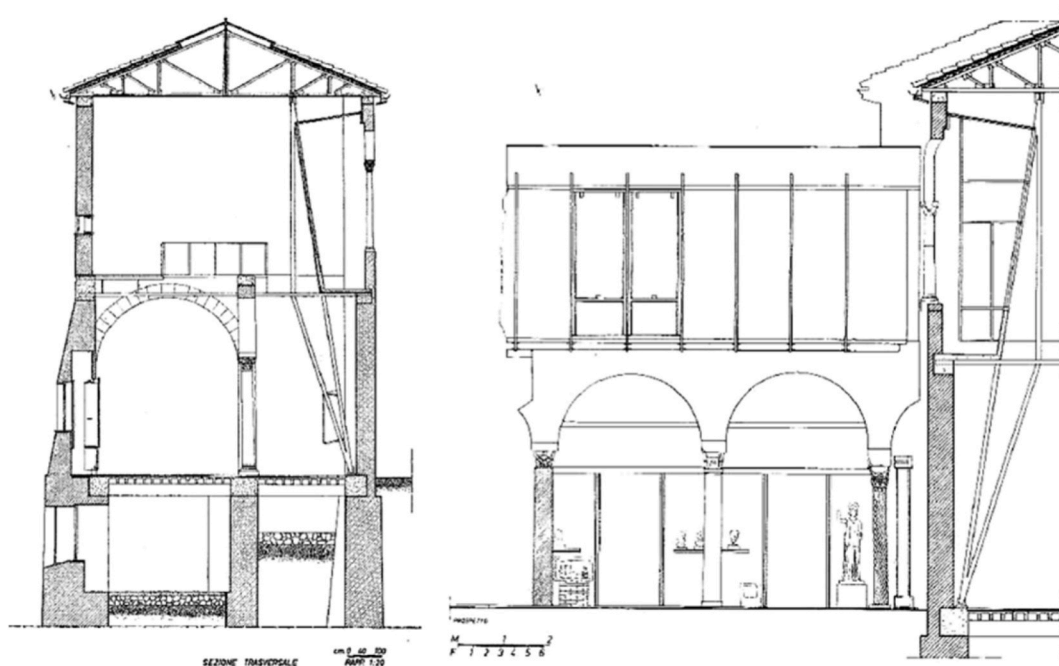


Fig. 6. Section of the Provincial Archaeological Museum after the restoration works.

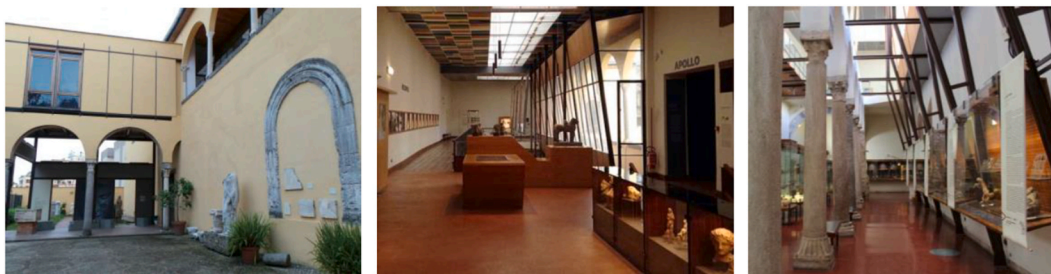


Fig. 7. Current state of the Provincial Archaeological Museum.

Table 8

Fire vulnerability of the Provincial Archaeological Museum.

CASE 2: CRITICALITY AND VULNERABILITY TO FIRE
Wooden elements: floor at the entrance porch, interior walkways, staircase, sloping wall coverings, furniture elements (glass cabinets, exhibition partitions, and seating)
Paintings along the museum tour
Signalization of escape routes
Inadequate ventilation of the space
Electrical safety system to be upgraded
Absence of automatic sprinkler system
Absence of detection and alarm system
Limited space in front and not easy access for emergency vehicles

automatic fire extinguishing system. I Linear smoke sensors will be installed, as well as a wireless public address system with automated sending of recorded voice messages and their specifications.

## 6. Application of the model to the case studies

Following the application of the model to the case studies, some interventions are not feasible due to some structural and functional building features. The application to the case studies led to reflections on the feasibility of some interventions (Tables 9 and 10).

The same application of Model A was conducted to case study 2, distinguishing between feasible and non-feasible interventions.

## 7. Discussion and results

The most suitable choice among the various compatible technical intervention solutions was identified through a comparison of those that achieve a comparable level of performance.

Following the potential interventions applicable to their respective case studies, the results are presented in Tables 11–14. A comparison was made between the pre- and post-operation satisfaction of fire safety retrofit interventions for both case studies, as shown in comparative Tables 11–12 (case study 1) and Table 13–14 (case study 2).

### 7.1. Proof of compliance with fire safety measures (MOD\_A)

Feasible interventions are highlighted in green, while non-feasible ones are highlighted in red. In case study 1 (St. Benedict Church), among the non-feasible interventions are fire-resistant compartment walls and SVOF (Smoke Venting and Outlet Fitting) and SEFC (Smoke and Evacuation Fan Control) systems for high-risk areas. The compartment walls are not feasible because the function requires a single large space dedicated to religious activities. Additionally, since there are no high-risk areas, the installation of smoke and heat exhaust systems is not anticipated. Furthermore, door replacement is not planned as the existing doors will be retrofitted. Similarly, for case study 2 (Provincial Archaeological Museum), not all technical solutions from the model are applicable. For example, fire-resistant compartment walls and SVOF and SEFC systems for high-risk areas are not feasible. The compartment walls are not feasible to preserve the internal space, and since there are no high-risk areas, there is no need for smoke and heat exhaust systems.

### 7.2. Proof of the compliance with conservation principles (MOD\_B)

Based on the threshold value determined in the methodology phase, the compatibility factor between fire safety interventions and restoration requirements should be above 93.80 %.

Following the application of the model, the results (presented in Tables 15 and 16, referring to case 1 and case 2 respectively) indicate that both cases exceed the minimum threshold of the compatibility factor with restoration requirements, which is 95.10 % for both case studies.

Regarding the compatibility of fire prevention interventions with restoration requirements, some seemingly incongruent results have emerged. For example, the fireproof treatment to enhance fire reaction and resistance received a low (negative) value in terms of reversibility but a high (positive) value in terms of non-invasiveness of the intervention. This apparent inconsistency can be explained

**Table 9**  
Feasible interventions.

Application of MOD_A to case study 1: feasible interventions
1.1–1.2: application of fire-retardant paint RU0010+RZ0020 (wooden materials)/application of intumescent paint PROMAPAINTE SC3 (non-visible materials)
1.5: storage of materials in suitable places
1.6: suitable sizing of fire-fighting equipment
1.7: monitoring high fire load areas
1.8: verification of opening sizing for high fire load areas
1.9: accessibility of areas with high fire load
1.10: application of KBS COATING insulating sleeves for electrical conduits/AUSTROFLEX FIREPROOF insulating cupels for gas pipes
2.1–2.2: application of KBS COATING insulating sleeves for electrical conduits/AUSTROFLEX FIREPROOF insulating cupels for gas pipes
2.3: use of KBS MORTAR sealing mortar for crossings
2.4: ordinary power supply separated from the safety supply for escape
2.5: automatic activation of systems in the event of an emergency
2.6: installation of automated opening/closing systems for doors and windows
2.7: EVAC system prepared for automated sending of recorded voice messages
2.9: location of facilities in easily accessible areas
2.10: application of KBS COATING insulating sleeves for electrical conduits/AUSTROFLEX FIREPROOF insulating cupels for gas pipes
3.1–3.2: application of fire-retardant paint RU0010+RZ0020 (wooden materials)/application of intumescent paint PROMAPAINTE SC3 (non-visible materials)
3.5: information of the personnel in charge
3.6: installation of automated opening/closing systems for doors and windows
3.7: correct placement of devices
3.9: ready availability of extinguishing agents
3.10: power supply network of high-risk areas separated from the ordinary one
4.1: removal of materials from escape routes
4.4: sizing of escape routes according to users
4.5: identification of shelter locations
4.6: elimination of obstructions to rescue teams
4.7: installation of linear smoke sensors for rooms with heights > 6 m
4.8: verification of correct positioning of openings for high fire load areas
4.9: Ensure the accessibility of emergency vehicles
4.10: Plants derived from the primary distribution network
5.1: compliance with safety distances
5.2: materials of a suitable strength class
5.3: compatibility with the character of the heritage building
5.4: self-closing doors and panic bars
5.5: appropriate organization and division of spaces
5.6: elimination of obstructions to rescue teams
5.7: installation of sensors on elements without historical-artistic value
5.9: removal of elements hindering fire-fighting operations
5.10: protection against electric shock
6.1–6.2: application of fire-retardant paint RU0010+RZ0020 (wooden materials)/application of intumescent paint PROMAPAINTE SC3 (non-visible materials)
6.3: suitable materials
6.4: materials belonging to the GM0 or GM1 group
6.5: fireproof materials
6.6: use of aerosol extinguishing agents with potassium salts from GREEN SAFETY
6.7: adaptation of any existing systems of the structure
6.9: Adaptation of escape stairs by protection/installation of external steel stairs
6.10: earthing system connected to possible conductor elements
7.1: correct installation of fire-fighting equipment
7.2: compatible fire-fighting equipment
7.3: correct sizing of fire-fighting equipment, for each compartment
7.4: installation of aerosol extinguishing system/CO2 extinguishers
7.5: use of aerosol extinguishing agents with potassium salts from GREEN SAFETY
7.6: installation of above-ground fire hydrants
7.7: mutual connection between installations via wireless technology

by the fact that the fireproof paint adheres to and becomes integral with the wooden substrate, and its removal would require the removal of the surface layer of the substrate. However, the application of transparent paint is considered a non-invasive intervention as it preserves the wooden element and does not involve the removal of material.

The results demonstrate the validity of the model in that, applied to both case studies, it provides the identical satisfaction value. The application of the model provides the designer with an additional useful tool for rapid identification of possible interventions to be made, in accordance with what are the characteristics of the structure and the contained assets.

## 8. Conclusion

Indicator-based methods can provide a simple and reliable way to assess the fire risk level of existing constructions. While many of

**Table 10**  
Unfeasible interventions.

Application of MOD_A to case study 1: unfeasible interventions	
1.3:	using FIREPANEL A1 gypsum fiber boards
2.8:	installation of SVOF and SEFC systems, limited to specific high-risk areas
3.3:	reducing the size of compartments
3.4:	installation of SVOF and SEFC systems, limited to specific high-risk areas
3.8:	installation of SVOF and SEFC systems, limited to specific high-risk areas
4.2:	compartments distinguished by homogeneous risk characteristics
4.3:	construction of firewalls with FIREPANEL A1 gypsum fiber panels, fixed on metal uprights, with mineral wool panel in between
5.8:	avoid interference of openings with other environments
6.8:	installation of any new lacquered wooden doors and windows
7.8:	mutual connection between headmasters and SVOF and SEFC systems via wireless technology

**Table 11**  
Pre- and post-intervention proof: application of model A to case study 1.

OBJECTIVES	STRATEGIES										Threshold level (n)	Strategies carried out (n)	Check
	1	2	3	4	5	6	7	8	9	10			
											6	1	Unsatisfied
											6	1	Unsatisfied
											6	1	Unsatisfied
											6	5	Unsatisfied
											6	5	Unsatisfied
											6	1	Unsatisfied
											6	0	Unsatisfied

**Table 12**  
Pre- and post-intervention proof: application of model A to case study 1.

OBJECTIVES	STRATEGIES										Threshold level (n)	Strategies carried out (n)	Check
	1	2	3	4	5	6	7	8	9	10			
											6	8	Satisfied
											6	9	Satisfied
											6	7	Satisfied
											6	8	Satisfied
											6	9	Satisfied
											6	9	Satisfied
											6	9	Satisfied

	Unsatisfied interventions in the state of the art
	Feasible adaptation measures
	Unfeasible upgrades

**Table 13**  
Pre- and post-intervention verification: application of model A to case study 2.

OBJECTIVES	STRATEGIES										Threshold level (n)	Strategies carried out (n)	Check
	1	2	3	4	5	6	7	8	9	10			
											6	1	Unsatisfied
											6	1	Unsatisfied
											6	1	Unsatisfied
											6	5	Unsatisfied
											6	5	Unsatisfied
											6	1	Unsatisfied
											6	0	Unsatisfied

these methods have not been specifically developed for cultural heritage assets, those that have often involve indicators linked to provisions defined by standards valid only in certain countries. Therefore, a method with the necessary flexibility to analyze the fire safety of cultural heritage assets is still needed [16].

The results of this research obtained from applying the model to the two Italian case studies, demonstrate that it is possible to achieve compliance with fire prevention parameters prescribed by recent national regulations through a performance-based approach while respecting the goals of restoration interventions, such as recognizability, reversibility, material compatibility, and non-invasiveness of the intervention. The developed model serves as a verification tool for designers to quickly identify possible

**Table 14**  
Pre- and post-intervention verification: application of model A to case study 2.

STATEGIES										Threshold level (n)	Strategies carried out (n)	Check
OBJECTIVES										6	8	Satisfied
										6	9	Satisfied
										6	7	Satisfied
										6	8	Satisfied
										6	9	Satisfied
										6	9	Satisfied
										6	9	Satisfied
Unsatisfied interventions in the state of the art Feasible adaptation measures Unfeasible upgrades												

**Table 15**  
Compatibility check of fire interventions with restoration instances (from the top, case 1 and case 2).

Application to Case study 1		RESTORATION AND CONSERVATION CRITERIA				
		Recognizability	Reversibility	Compatibility	Non-invasiveness	Average satisfaction
STRATEGIES	Fire reaction	7/7	3/7	7/7	7/7	86%
	Fire resistance	6/6	3/6	6/6	6/6	88%
	Compartmentation	4/4	4/4	44	4/4	100%
	Escape	6/6	6/6	6/6	6/6	100%
	Fire safety management	7/7	7/7	7/7	6/7	96%
	Fire control	5/7	7/7	7/7	6/7	89%
	Detection and alarm	7/7	7/7	7/7	7/7	100%
	Smoke and heat control	2/2	2/2	2/2	2/2	100%
	Fire operation	7/7	7/7	7/7	6/7	96%
	Safety of technological and service facilities	7/7	6/7	7/7	7/7	96%
<b>Compatibility Factor with the Restoration and Conservation Criteria</b>						95,10%

**Table 16**  
Compatibility check of fire interventions with restoration instances (from the top, case 1 and case 2).

Application to Case study 2		RESTORATION AND CONSERVATION CRITERIA				
		Recognizability	Reversibility	Compatibility	Non-invasiveness	Average satisfaction
STRATEGIES	Fire reaction	7/7	3/7	7/7	7/7	86%
	Fire resistance	6/6	3/6	6/6	6/6	88%
	Compartmentation	4/4	4/4	44	4/4	100%
	Escape	6/6	6/6	6/6	6/6	100%
	Fire safety management	7/7	7/7	7/7	6/7	96%
	Fire control	5/7	7/7	7/7	6/7	89%
	Detection and alarm	7/7	7/7	7/7	7/7	100%
	Smoke and heat control	2/2	2/2	2/2	2/2	100%
	Fire operation	7/7	7/7	7/7	6/7	96%
	Safety of technological and service facilities	7/7	6/7	7/7	7/7	96%
<b>Compatibility Factor with the Restoration and Conservation Criteria</b>						95,10%

intervention alternatives in line with the characteristics of the structure and its contents. The study also highlights the interdisciplinary approach to intervention by combining different requirements (compliance with fire safety regulations while respecting restoration criteria) in a performance-based approach to achieve the primary objectives of fire safety improvement in a historic building: reducing risks to people and immovable property (building and its contents).

This work also aims to guide designers towards a careful and thoughtful use of materials and selection of intervention techniques compatible with the structure and its contents, while considering aspects of environmental compatibility and occupant health. The study advocates for the use of ecological materials (i.e., materials that do not emit harmful fumes in case of fire) and eco-friendly

materials (with the goal of reducing greenhouse gas emissions throughout their life cycle). At the same time, cost control measures are emphasized to manage expenses and address economic uncertainties often associated with interventions on monumental buildings.

The results, which are largely similar between the two analysed case studies, demonstrate the applicability of the methodology to various types of protected assets, including museums, galleries, buildings for exhibitions or shows, libraries, and archives, as defined in Italian cultural heritage legislation.

The developed evaluation model does have certain limitations in terms of validation, as there are no comparable models in literature. Furthermore, the study's limitations extend to the examination of a limited number of cases in relation to the numerous possible alternatives, including building types, usage, dimensions, construction systems, or materials.

Compared to the state-of-the-art analysis, the proposed methodology is innovative as it combines the need for a prescriptive approach with the requirement for a performance-based approach while ensuring the safeguarding of historic buildings. The practical application could involve the design of a database to support fire prevention assessment methods [23].

The novelty of the research lies in providing an original contribution to a complex and singular field governed by the specificity of the case study. It can define some repeated parameters of risks and losses to propose an evaluation model applied and tested in two historic buildings with satisfactory results that can be extrapolated to other case studies.

This is perhaps one of the earliest contributions on the subject and opens a new field of research and work for further study. Subsequent developments may involve broadening the set of case studies and involving factors related to social theory and human behaviour in the face of hazardous situations.

### Declaration of competing interest

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

### Data availability

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

### References

- [1] L. Wilson, A. Rawlinson, A. Frost, J. Hefher, 3D digital documentation for disaster management in historic buildings: applications following fire damage at the Mackintosh building, the Glasgow School of Art, *J. Cult. Herit.* 31 (2017) 24–32, <https://doi.org/10.1016/j.culher.2017.11.012>.
- [2] A. Iringová, in: F. Zafar, A. Ghosal (Eds.), *A Case Study on the Fire Safety in Historic Buildings in Slovakia*, Fire Safety and Management Awareness, Intechopen, London, 2020, <https://doi.org/10.5772/intechopen.91241>.
- [3] J.L. Torero, Fire safety of historical buildings: principles and methodological approach, *Int. J. Architect. Herit.* 13 (7) (2019) 926–940, <https://doi.org/10.1080/15583058.2019.1612484>.
- [4] F. Ribera, P. Cucco, Ricomporre i frammenti, Distruzioni, ricostruzioni, trasformazioni, EdA - esempi di Architettura, *Int. J. Architec. Eng., Special Issue* (2021) 7–18, <https://doi.org/10.53136/97912599461642>.
- [5] M. Calzolari, S. Marsella, Il progetto del sistema antincendio della Basilica di San Paolo fuori le mura a Roma: un caso di sicurezza antincendio del XIX secolo, in: S. D'Agostino (Ed.), *F. R. d' Ambrosio History of Engineering - Proceedings of the 3rd International Conference, Naples, 2018 April 23-24th*, Cuzzolin, Naples, 2018, pp. 439–447.
- [6] D.F. Venegas, C. Ayabaca, O. Erazo, O. Farias, A. Madina, Fires in world heritage buildings, *Artif. Intell.* 1 (2021) 1–15, [https://doi.org/10.1007/978-3-030-68080-0\\_32](https://doi.org/10.1007/978-3-030-68080-0_32).
- [7] A. Calia, D. Colangiuli, M. Lettieri, M. Masieri, Microscopic techniques and a multi-analytical approach to study the fire damage of the painted stuccoes from the Petruzzelli Theatre (Bari, Southern Italy), *Microchem. J.* 126 (2016) 42–53, <https://doi.org/10.1016/j.microc.2015.11.049>.
- [8] G. Bernardini, M. Azzolini, M. D'Orazio, E. Quagliarini, Intelligent evacuation guidance systems for improving fire safety of Italian-style historical theatres without altering their architectural characteristics, *J. Cult. Herit.* 22 (2016) 1006–1018, <https://doi.org/10.1016/j.culher.2016.06.008>, 2016.
- [9] A. Vallée, E. Sorbets, H. Lelong, G. Langrand, J. Blacher, The lead story of the fire at the Notre-Dame cathedral of Paris, *Environ. Pollut.* 269 (2021) 116–140, <https://doi.org/10.1016/j.envpol.2020.116140>.
- [10] A. Guibaud, J.-C. Mindeguia, A. Albuerno, T. Parent, J. Torero, Notre-Dame de Paris as a validation case to improve fire safety modelling in historic buildings, *J. Cult. Herit.* (2023), <https://doi.org/10.1016/j.culher.2023.05.008>.
- [11] G. Bernardini, Fire Safety of Historical Buildings. Traditional versus Innovative “Behavioural Design” Solutions by Using Wayfinding Systems, *SpringerBriefs in Applied Sciences and Technology*, 2017, <https://doi.org/10.1007/978-3-319-55744-1>.
- [12] S. Kincaid, Fire prevention in historic buildings – approaches for safe practice, *Hist. Environ.: Pol. Pract.* 13 (2022) 361–380, <https://doi.org/10.1080/17567505.2022.2098633>.
- [13] A. Wolski, N.A. Dembsy, B.J. Meacham, Accommodating perceptions of risk in performance-based building fire safety code development, *Fire Saf. J.* 34 (3) (2000) 297–309, [https://doi.org/10.1016/S0379-7112\(00\)00003-5](https://doi.org/10.1016/S0379-7112(00)00003-5), April 2000.
- [14] BS 9999, *Code of Practice for Fire Safety in the Design, Management and Use of Buildings*, British Standards Institution (BSI), 2008.
- [15] P. Cancelliere, M. Lombardi, L. Ponticelli, M. Caciolai, et al., Italian hybrid fire prevention code - september 2017, in: *Conference: SAFE 2017 7th International Conference on Safety and Security Engineering*, Rome University La Sapienza, 2017, <https://doi.org/10.2495/SAFE170101>.
- [16] L.G.F. Salazar, X. Romao, E. Pauperio, *Int. J. Disaster Risk Reduc.* 60 (2021), 15 June 2021, 102286 - International Journal of Disaster Risk Reduction.
- [17] P. Cancelliere, L. Palmeri, E. Gissi, CODICE DI PREVENZIONE INCENDI COMMENTATO a cura di Fabio Dattilo e Cosimo Pulito - Publisher: EPC S.r.l. Socio Unico Editor, EPC Editore ISBN, 2015, 978-88-6310-684-8.
- [18] M.J. Hurley, *SFPE Handbook of Fire Protection Engineering*, Springer V ed., New York, 2016.
- [19] M. Pasca, *Il Centro Storico di Salerno*, Beta Gamma Editrice, Viterbo, 2000.
- [20] F. Ribera, P. Cucco, A methodology in choosing a new compatible function in the recovery project of disused religious buildings, *Res. Stud. Italy, VITRUVIO 1* (2020) 1–15. WOS:000541853800002.
- [21] E. De Felice, *Il Museo provinciale di Salerno nell'abbazia di San Benedetto, Alfieri e Lacroix*, Milan, 1966.
- [22] E. De Felice, *Luce - Musei*, De Luca Editore, Rome, 1966.
- [23] K. Peffers, T. Tuunanen, M.A. Rothenberger, S. Chatterjee, A design science research methodology for information systems research - january 2007, *J. Manag. Inf. Syst.* 24 (3) (2007) 45–77.