DEVELOPMENT OF A FIRE DAMAGE INDEX FOR IMMOVABLE CULTURAL HERITAGE

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Keywords: Fire Damage Impact Index, Immovable Cultural Heritage, Vulnerability Assessment

Abstract. *Available fire risk assessment approaches are mostly developed for new buildings. These approaches encompass minimum provisions defined by standards that are valid in certain countries, and few of these methods were thought exclusively for assessing the fire safety of cultural heritage. Given the diversity and specificity of cultural heritage assets, simple approaches are thus required to analyse their fire safety and establish their risk mitigation needs. In this context, a simplified fire damage index dedicated to assessing the fire vulnerability of immovable cultural heritage assets is proposed. The proposed index is the result of a weighted multi-parameter evaluation that can be correlated with the level of damage that the cultural heritage asset (including its contents) is expected to suffer under a fire. The proposed index involves twenty-one indicators divided into four categories and offers a flexible approach for universal applicability. The performance of the proposed approach is illustrated for two case studies in Portugal. The results highlight the advantages of having a simple methodology that can be used for the preliminary risk analysis of a large number of assets to identify those requiring risk mitigation measures or detailed and resource-demanding analyses.*

1 INTRODUCTION

Fires that affected cultural heritage assets in recent years (e.g. the National Museum of Rio de Janeiro (Brazil) in 2018, and of the Cathedral of Notre Dame (France) in 2019) emphasise the need for more studies related to their fire safety. The occurrence of these fires can be connected to various factors ranging from a general lack of maintenance, to a lack of adequate safety measures during restoration works. Moreover, historic constructions exhibit a higher fire vulnerability since they were constructed without considering fire preparedness measures, namely aspects commonly considered in current construction standards such as adequate evacuation routes or emergency exits. The combustible nature of many cultural heritage elements often forces stakeholders to address these issues by integrating modern fire protection

systems in historic constructions. However, the integration of such systems needs careful consideration to avoid the loss of cultural heritage values due to their installation, as well as the occurrence of further damage during their use (e.g. water sprinkler systems in scenarios involving cultural heritage assets sensitive to water damage).

Several methods have been developed to assess fire risk in buildings, but most of the robust approaches were developed for new buildings and involve formulations that are not compatible with cultural heritage values or are exclusively for one type of heritage. The development of a robust fire safety assessment method for multiple cultural heritage assets is thus needed, namely one that accounts for both the building and its cultural contents, and that can be implemented in any country. To address this need, a fire damage impact index of vulnerability is proposed herein. The index is presented in the following and some of its components are detailed for the case of single cultural heritage assets (i.e. assets physically separated from other assets or constructions) that can host movable heritage or have heritage elements attached to the main asset. Typical examples of such heritage assets are historic houses, religious buildings or museums. Following the description of the proposed index, an application to two real cases with different expected damage impacts if case of fire is also presented.

2 FIRE DAMAGE INDEX METHODOLOGY

The proposed index was developed following a thorough literature review focusing, in particular, methods that gave more emphasis to historical constructions. The indicators selected for the fire index were determined by examining international statistics concerning the causes of multiple fires, existing fire risk assessment methods, as well as checklists and standards providing guidance on fire prevention. The general type of indicators that were selected can be seen to generally be in agreement with those considered by other fire risk assessment methods for historical constructions [1-7]. This fire index assesses the expected Level of Damage (D_V) in case of fire, ranked in three levels (i.e. light $(0 \leq D_V \leq 35)$, medium $(35 \leq D_V \leq 70)$, and heavy $(70 \leq D_V \leq 100)$). Light damage refers to cases where the cultural asset is expected to sustain negligible damage and safety is ensured, but a regular monitoring of the situation is recommended. Medium damage refers to situations where the cultural asset can suffer damage that may be partially recovered in case of fire. Heavy damage refers to cases that may involve irreparable damage or the total loss of the cultural asset. The proposed index is compatible with the Level of Vulnerability (V_L) assessment proposed by [8] that integrates a factor of easiness of reparation and restoration (R_f) and a heritage value factor (BV_f) and can be defined as:

$$V_L = D_V \times R_f \times BV_f \tag{1}$$

The fire index establishes the relevance of all the twenty-one indicators divided into four groups (G_i) (building properties (BP); utilities: electric power, gas and telecommunications (UEPGT); firefighting measures (FM); emergency preparedness planning (EPP)). Each indicator is assigned to one of five damage impact classes (very low (A), low (B), moderate (C), high (D), and very high (E)). The classification of a group corresponds to that of the indicator that exhibits the worst performance. This assumes that the bad performance of one indicator within a group is enough to intensify the susceptibility of having an ignition, the fire propagation or the difficulty to fight fire. The classes (C_i) are then scored with values of 0 (A), 25 (B), 50 (C), 75 (D), 100 (E). The final index is then obtained by a weighted combination of

the classification of each group. Based on the literature review, weights of 35 %, 20 %, 30 % and 15 % were defined for BP, UEPGT, FM and EEP, respectively.

2.1 Building Properties (BP)

Indicators of this group refer to different aspects related to the physical properties of the building (material properties, geometrical properties, spaces and their separation, the existence of combustible materials), except installations considered in the UEPGT, and to its immediate surrounding area. Physical properties are relevant for fire risk assessment in terms of their fire resistance, combustibility and the amount of fire load that they represent (considering movable contents and building materials). Moreover, spaces (corridors, halls, rooms, etc.) and their separation provide information related to fire propagation. Indicators in this group are the fire load density (P_1), the fire resistance (P_2), the compartmentalisation (P_3), the type of adjacent buildings (P_4), the possibility of vertical fire propagation (P_5), the building conservation status (P_6), the existence of fire breaks/buffer zones (P_7) according to:

$$G_1 = BP = [Max\ (P_{i,i=1:7})] \times 0.35 \tag{2}$$

For this simplified assessment, P_1 is defined using values from the literature for historical constructions as the sum of two components: the immovable load density I_q and the movable contents M_q related to the building use. Parameter I_q is defined by the combustibility of constructive materials. Combustible materials are, for example, timber, textile, organic materials, plastics, resins, while non-combustible materials are clay, soil, concrete, gypsum, steel or stucco. Based on the literature review [9, 10], I_q was defined according to the predominant combustible or non-combustible material of the historical construction under assessment (Table 1). Parameter M_q is determined by the current use of the historical building (Table 2). These and other values can be found in [11, 12].

Table 1: Values proposed for parameter I_q.

Type of structure (Finishes and Supports)	Fire Load
Structure made with a least 80% of combustible materials, e.g. floors and walls made of timber.	3,000 MJ/m^2
Structure made with a balance of non-combustible and combustible materials, e.g. masonry walls and timber floors or thatch roofs.	1,100 MJ/m^2
Structure made with at least 80% of non-combustible materials, e.g. masonry walls and reinforced concrete slabs.	200 MJ/m^2

Table 2: Values proposed for parameter M_q according to the building activity.

Type of Use (Current activity)	Fire Load	Type of Use (Current activity)	Fire Load
Housing/Apartment/Dwelling	780 MJ/m^2	Officine	1,200 MJ/m^2
Museum/Art galleries	300 MJ/m^2	Hotels, Hospitals	300 MJ/m^2
Churches (furniture and candles)	1,300 MJ/m^2	School	300 MJ/m^2
Libraries/Archives	1,500 MJ/m^2	Shopping/Cinema/Theatre	800 MJ/m^2

Parameter P_2 is defined based on [13, 14] to be consistent with the European Reaction to

Fire classification system. The classification is based on the predominant material as for I_q, and its susceptibility to produce flashover according to seven types (A1, A2, B, C, D, E and F). From A1 to F, materials have a decreasing fire resistance, thus a higher likelihood of producing a flashover. Parameter P_3 is related to the possibility of containing the occurrence of a fire within certain areas of the building to avoid its propagation, and reflects the size of the largest fire compartment with combustible or flammable materials. The lack of containment elements between compartments (i.e. doors) can lead to an increase of the class of P_3 by one level. The classification of this parameter is based on criteria defined in [7, 14] but accounts for other features such as the existence of self-closing doors or windows. When there are self-closing systems, the classification of P_3 can be reduced by one level (e.g. if the compartmentalisation classification leads to Class B, it can be upgraded to Class A if there are self-closing systems).

Parameter P_4 reflects the influence of adjacent buildings according to their location and type of construction (i.e. in terms of combustible materials). Following the distance criteria in [15], P_4 is classified as type IS if the construction under assessment has no surrounding constructions with exposed combustible materials closer than 12m, made of timber closer than 6m, or made of quasi-fire resistant materials closer than 3m. Otherwise, P_4 is classified as type IC. P_4 can also be classified as AC if there are adjacent constructions made mostly with combustible materials, as ACN if there are adjacent constructions made with a balance of combustible and non-combustible materials, or as AN if there are adjacent constructions made with non-combustible materials. When the adjacent constructions are abandoned, P_4 is increased by one level. The classification of parameter P_5 reflects the likelihood of vertical fire propagation within the construction under assessment, depending on the geometric proportion and number of vertical aligned openings. This parameter is graded by the ratio $r = l/h$ and the number of levels between openings (nl), where l is the vertical distance between openings and h is the height of the opening of the lower level [14] (see Table 3). The same ratio r is also used to analyse the relation between openings of the top building level and a roof structure made of combustible material. The classification of P_5 can be reduced by one level if the construction material is combustible but was upgraded to have a reasonable fire resistance. When a construction presents situations with both $r \geq 1$ and $r < 1$, P_5 can be graded as C, regardless of the number of levels. In case there are no aligned openings and roofs have non-combustible materials (NAI), P_5 can be graded as A. Parameter P_6 reflects the level of conservation and cleanliness of the construction's combustible materials (e.g. timber, thatch, or bamboo). This parameter is graded according to five levels ranging from Very Good (when there are no combustible materials in the building), Good (when the combustible materials are in good condition and have a fire-resistance finishing), Medium (when the combustible materials appear to be in good condition, without any type of biological colonisation (i.e. termites) and high porosity), Bad (when the materials exhibit high porosity produced by biological colonisation), and Very Bad (when the combustible materials exhibit high concentration of humidity, biological colonisation, porosity, and vegetation growth; a common situation in abandoned historical constructions). Parameter P_7 reflects the horizontal propagation of fire from exterior combustible materials through the distance between the construction under assessment and the surrounding vegetation, rubbish or other elements that may exist. In the case of surrounding vegetation, based on criteria from the United States National Fire Protection Association and recommendations from the Portuguese Civil Protection, P_7 was graded from A to E when the

referred distance is more than 50m, between 50m and 30m, between 30m and 5m, from 5m to 1.5m, and less than 1.5m, respectively. P_7 is also associated with the criteria used by [15] which involve the critical distance between constructions made of combustible materials defined by types I to IV. In this case the critical distance is defined with respect to other possible exterior combustible materials, namely street furniture, rubbish or other elements that are not vegetation or other constructions. Types I to IV correspond to cases where the distance from ignition sources is more than 12m, between 12m and 6m, between 6m and 3m, and less than 3m, respectively. The classification of P_7 can be reduced by one level if the heritage asset near combustible or flammable materials is made of non-combustible materials. Table 3 summarizes the classifications of indicators P_1 to P_7.

Table 3: Classification of parameters P_1 to P_7.

Indicator	Class					Units
	A	**B**	**C**	**D**	**E**	
	0	**25**	**50**	**75**	**100**	
P_1	<500	500-750	750-1500	1500-3000	>3000	MJ/m^2
P_2	A1	B2	B	C, D	E, F	-
P_3	<50	50-100	100-200	200-400	>400	m^2
P_4	IS or AN	IC	ACN	AC	ACA	-
P_5	NAI	$r \geq 1$	$r \geq 1$ and $r<1$	$r<1$ and $nl \leq 2$	$r \leq 1$ and $nl>2$	-
P_6	Very Good	Good	Medium	Bad	Very Bad	-
P_7	>50 and I	50-30 or II	30-5 or III	5-1.5 or IV	<1.5 and IV	m

2.2 Utilities: Electric Power, Gas and Telecommunications (UEPGT)

The second group of parameters is related to the characteristics and components of the existing utilities that can facilitate the occurrence or propagation of a fire due to their maintenance conditions or contribute to increase the overall fire safety. It must be noted that some of these utilities that were not part of the original cultural heritage asset are often found to be operating under inadequate safety conditions (e.g. unprotected electrical wiring or electrical overload of power outlets). These unsafe conditions increase the vulnerability of the construction and its contents. The UEPGT group considers five indicators related to the electrical (P_8), gas (P_9), HVAC (P_{10}), telecommunications and CCTV systems (P_{11}), to the technical control room (P_{12}), and that are combined according to:

$$G_2 = UEGPT = [Max\left(P_{i,i=8:12}\right)] \times 0.20 \tag{3}$$

The classification of parameter P_8 follows principles referred in [6, 16] to reflect the level of maintenance of the electrical installation. The grading levels (see Table 5) are Excellent (EX) (adequate isolation of electrical components and combustible materials installed by professionals), Good (G) (refers to installations similar to EX but not installed by professionals), Medium (M) (installation with both new and older electrical components), Bad (BA) (installation with older electrical components only), and Very Bad (VB) (installation similar to BA but with known electrical deficiencies). The deficient implementation of a lightning rod in buildings with tall vertical elements (e.g. a bell tower, pinnacle or cupola) can also be considered to increase the classification of P_8 by one level [17]. Parameter P_9 is graded

in Table 4 according to the type of gas supply [6], which can be piped (P), a gas reservoir (GR), an external gas container (EGC), an internal gas container in a well-ventilated area (IGCV), or an internal gas container in a poorly-ventilated area or close to heat sources (IGCNV). The absence of gas installations is graded as A. The classification of P_9 is increased one level when gas installations or gas heaters are near flammable materials. Parameter P_{10} reflects the existence of an HVAC system, that could be decentralized (D) or centralized (C). If the system exhibits a good working condition P_{10} is graded as B (see Table 4). If the system's level of maintenance is inadequate, the classification increases to C for a decentralized system (DCF) and to D for a centralized system (CCF). These classifications increase one more level if the system is near combustible or flammable materials (to LMD and LMC for decentralized and centralized systems, respectively). The absence of HVAC (NH) is equivalent to Class A. Parameter P_{11} combines information related to the likely level of criminality of the area of the construction under assessment and to the availability of systems with automatic communication with the fire brigade services and video surveillance (CCTV). Parameter P_{11} is thus graded in Table 4 as TT1 when there is a good CCTV system in low criminality zones, TT2 when there is a good CCTV system in moderate or high criminality zones, TT3 when there is an incomplete CCTV system (i.e. cameras are not available in all the relevant spaces), and TT4 when there is no adequate CCTV system. The TT1-TT4 grading assume there is an efficient communication system with the fire brigade. If this condition is not met, the classification can increase one level. A grading TT5 is assigned when there is no CCTV system and no automatic communication system with the fire brigade.

Table 4: Classification of parameters P_8 to P_{12}.

Indicator	Class				
	A	**B**	**C**	**D**	**E**
	0	**25**	**50**	**75**	**100**
P_8	EX	G	M	BA	VB
P_9	P	GR	EGC	IGCV	IGCNV
P_{10}	NH	D or C	DCF	CCF or LMD	LMC
P_{11}	TT1	TT2	TT3	TT4	TT5
P_{12}	Out≥5	Out<5	IMC	IMM	IB

Due to the flammability of components that a technical control room can have, its contribution to the impacts is assessed independently by P_{12} (Table 5). This parameter reflects the location of the technical control room within the construction under assessment, its degree of maintenance, and the fire-resistant nature of the surface materials. When the technical control room is located outside the main construction at a distance more than 5m, P_{12} is assigned to Class A, whereas when the engine room is located at a distance equal or less than 5m, P_{12} is assigned to Class B. Assigning P_{12} to Class C (IMC) corresponds to cases where the technical control room is inside the construction and exhibits a good condition and there are some fire control systems in place (e.g. an active suppression system, fire-retardant materials, or self-closing doors). If the technical control room is located inside the construction and exhibits a good condition but there are no active or passive fire suppression systems, class D (IMM) is assigned. If the technical control room does not exhibit a good condition or there are no fire suppression systems, P_{12} is assigned to class E (IB). If there are flammable elements or

combustible materials that are not associated to the functionality of the technical control room (e.g. textiles, mattresses, candles, ropes), the classification of P_{12} is increased one level.

2.3 Firefighting measures (FM)

The firefighting measures involves five parameters graded according to Table 5 and combined according to Equation 4. This group addresses the existence of alarm and detection systems (P_{13}), of smoke control systems (P_{14}), of active suppression systems (P_{15}), of water supply systems (P_{16}), and the site accessibility by and its proximity to fire rescue services (P_{17}).

$$G_3 = FM = [Max\left(P_{i,i=13:17}\right)] \times 0.30 \tag{4}$$

Parameter P_{13} reflects the existence of an efficient alarm and fire detection system where all components are in good working condition (except when stated otherwise). The grading of P_{13} involves the classes AM (when there is a dual (automatic and manual) system in all the relevant zones of the construction under assessment), AA (when there is only an automatic system), AMN (when there is a dual system with deficiencies in the automatic component), AAN (when there is only an automatic system that is not in perfect working conditions), and NAD (when there is no system). The classification of P_{13} can increase one level when there is a significant likelihood of false alarms. Parameter P_{14} refers to the existence of smoke control systems in enclosed compartments (automatic systems, through the spatial arrangement of the building, or both) that can facilitate evacuation or firefighting actions [18]. Parameter P_{14} is graded as SC1 (when there are active and passive systems in good working conditions), SC2 (when there is only a functional active system in corridors, stairs, or elevator shafts), SC3 (when there is only passive extraction systems), SC4 (when there is a partially working SC2 or SC3 system) and SC5 (when there are no smoke control systems). Parameter P_{15} reflects the existence of active fire suppression systems that have any of the following components: sprinklers, extinguishers, hydrants, hose reels, wet and dry rising mains, drencher systems, sparge pipes, water curtains, or foam systems. Parameter P_{15} is graded as AS1 (when there are firefighting systems in evacuation routes and inner compartments that will not affect water-sensitive movable assets in case of a fire), AS2 (when there are firefighting systems in locations that can affect water-sensitive movable assets in case of a fire), AS3 (when there are only fire suppression systems in evacuation zones), AS4 (when there are suppression systems that have faulty or unreliable components), and AS5 (when there is no firefighting equipment). Parameter P16 addresses the water supply systems that include interior (e.g. water tanks) or exterior (e.g. fire hydrants, rivers, lakes, etc.) water sources. Parameter P_{16} is graded as W1 (when the supply can be either from the interior of the construction under assessment with a well-designed water tank or from its exterior by a source with enough capacity (e.g. at least 20 m^3), that is closer than 20m), W2 (when the source is from an interior water tank with insufficient capacity, and exterior sources closer than 10m), W3 (when all the possible exterior sources are between 10m and 20m away), W4 (the possible exterior sources are between 20 and 40m away), and W5 (when there are no interior or exterior sources for water supply). In situations where the exterior water sources are fundamental, and if their availability is known to be scarce or water is frozen in specific times of the year, the classification of P_{16} should increase by two levels. When the fire suppression system presents an adequate automatic non-water-based alternative, P_{16} can be graded as W1. With respect to parameter P_{17}, the selected criteria are based on the firefighters' expected time

of arrival at the construction under assessment, partially based on [19] (see Table 5). When P_{17} is graded as E or D, this construction can be reduced two levels if P_{13}, P_{15} or P_{16} are of Class A (e.g. if the construction has AM, AS1, W1 and $P_{17} > 40\ min$, P_{17} should be graded as C). The grade of P_{17} increases one level if the access to the façade of the construction has physical obstacles, if there is a unique or no road access, or if the access routes have heavy traffic.

Table 5: Classification of parameters P_{13} to P_{17}.

Indicator	Class					Unit
	A	**B**	**C**	**D**	**E**	
	0	**25**	**50**	**75**	**100**	
P_{13}	AM	AA	AMN	AAN	NAD	-
P_{14}	SC1	SC2	SC3	SC4	SC5	-
P_{15}	AS1	AS2	AS3	AS4	AS5	-
P_{16}	W1	W2	W3	W4	W5	-
P_{17}	0-10	10-20	20-30	30-40	>40	min

2.4 Emergency Preparedness Planning (EPP)

This group reflects the availability of measures and strategies implemented to safeguard the construction and its movable assets given their cultural value. This group integrates parameters addressing the existence of emergency planning (P_{18}), the elevation of relevant compartments of the construction (P_{19}), evacuation routes (P_{20}), and emergency signage (P_{21}) according to:

$$G_4 = EPP = [Max\ (P_{i,i=18:21})] \times 0.15$$

(5)

Parameter P_{18} is graded as EA when the staff is trained to handle emergency situations and there is an emergency response plan with measures for the evacuation or protection of cultural assets in case of fire and specific procedures for the fire brigade that will deal with the fire [16]. This emergency response plan needs to involve guidance for staff training, information about the governance hierarchy and the control of access to the construction during emergencies, guidance for the evacuation of cultural assets during emergencies and procedures to carry out regular safety/risk assessments. The emergency plan, must have strategies to address scenarios where rehabilitation or refurbishment operations that may involve hot works are carried out [18]. If the emergency plan only accounts for the safety of people, P_{18} is graded as EB. P_{18} is graded as EC when the staff is trained to handle emergency situations, but there is no emergency plan. P18 is graded as ED when there is an emergency plan but the staff is not trained to handle emergencies. If there is no emergency plan and if the staff is not trained to handle emergencies, P_{18} is graded as EE. Parameter P_{19} is linked to the elevation of the habitable space (HS) or the compartments with cultural assets (CUA), considering the most disadvantageous case (see Table 6). The classification of P_{19} can be modified when CUA and/or HS are located at a height over 9 m but there are active suppression systems (AS1 or AS2) and when efficient strategies of staff training are also integrated into the emergency plan (EA) [18]. Parameter P_{20} combines multiple factors (i.e. travel distance to safety points (*d*), the width of corridors (*w*) and their slope (*s*)) based on [5, 16], to reflect the characteristics of the evacuation routes relevant for the evacuation of movable assets (from A to E), or for people (from B to E). If P_{20} is classified as D or E, it can be improved by one level (up to three) each time one of the following are

available: efficient active suppression systems (AS3), smoke control systems (SC1, SC2 or SC3) and EA in evacuation zones or specific meeting points. On the other hand, P_{20} is increased by one level when there are combustible materials obstructing evacuation routes. Parameter P_{21} considers the contribution of signage and emergency lights to the safeguard of movable assets and the safety of people during an emergency. When there are emergency lights in the evacuation routes (EL) and the signage provides instructions for both the safeguard of movable assets (SM) and the safety of people (SP) during an emergency, P_{21} is of class A. When there are emergency lights in the evacuation routes (EL) but the signage only addresses the safety of people (SP), P_{21} is of class B. When there is only one element (i.e. emergency lights or signage) that provides the safeguard of movable assets (SM) and the safety of people (SP) during an emergency, P_{21} is of class C. When there is only signage addressing the safety of people (SP), P_{21} is of class D. When there are no emergency lights and signage (N), P_{21} is of class E. If the emergency lights are not in good working condition, P_{21} increases by one level.

Table 6: Classification of parameters P_{18} to P_{22}.

Indicator	Class				
	A	**B**	**C**	**D**	**E**
	0	**25**	**50**	**75**	**100**
P_{18}	EA	EB	EC	ED	EE
P_{19}	CUA ≤ 7 m and HS ≤ 9 m	HS and CUA ≤9 m, or CUA and HS >9 m and AS1 and EA	HS or CUA>9 m and AS1/AS2 and EA	HS or CUA>9 m and EA	HS and/or CUA >9 m
P_{20}	s=0-5°	s=0-5°	s=0-5°	s>15°	s>15°
	d≤15 m and w>3 m	d≤20 m or w>3 m	d>20 m and w>3 m	d>20 m or w<3 m	d>20 m and w<3m
P_{21}	SM and SP and EL	SP and EL	SP/SM or EL	SP	N

3 APLICATION OF THE PROPOSED METHODOLOGY

3.1 Description of the case studies

The first case study is the 16th century Church of Misericordia in Esposende, Portugal, (41°31'51.85"N, 8°46'50.18"W). Based on data available from an in-situ survey, the BP group was classified as D. The church exhibits a balance between combustible (i.e. main and secondary altars, roof, mezzanine and stairs made of timber (see Figure 1a)) and non-combustible materials (i.e. stone walls), and its current use is religious with an archive, thus leading to an estimated fire load for P_1 of 2600 MJ/m^2 (Class D). P_2 was graded as C, considering since the unprotected timber, namely, in the altars and the furniture, is a fire susceptible material. P_3 is graded as C since the largest compartment size is approximately 103 m^2, whereas P_4 is equal to A since the church is an isolated construction. The ratios r that were evaluated lead to a P_5 of Class C. Due to the level of degradation exhibited by some combustible materials and the lack of intumescent materials, P_6 is graded as C. For P_7, E was assigned due to a tree located approximately 4.48 m from one of the entrances (see Figure 1b). UEGPT was assigned to Class E due to P_8, and P_{12}. The former is graded as E because there are extension cords close to the combustible materials behind the main altar (see Figure 1c), and there are

frequent power surges when many electric components are turned on. The existence of gas containers stored in a poorly-ventilated area inside the building (see Figure 1d) and the use of gas heaters during ceremonies leads to a class D for P_9. The building does not have a HVAC system, leading to P_{10} of Class A. Since the building has a few cameras in the interior, P_{11}, is graded as C. P_{12} was graded as E due to a lack of fire suppression systems and the fact there is a mattress located in the compartment of the electrical control panel. FM was assessed as E due to a lack of fire detection (P_{13}), smoke control (P_{14}) and fire suppression systems (P_{15}). Still, P_{16} is graded as C (there is an exterior fountain 10m away and a public hydrant at approximately 20m), and P_{17} is graded as B (the firefighter services are nearby). Even though the height of the upper level is lower than 7m (P_{19} is A), EPP was graded as E due to a lack of emergency planning (Class E), the travel distance being more than 20m (Class E), and the door widths being lower than 3m (Class E). The absence of signage and the presence of emergency lights that are not in good working conditions lead to P_{21} of Class D. Table 7 and Figure 3a summarize the assessed parameters and present a final damage level D_V of 91.25 (heavy damage).

Table 7: Fire Risk Assessment Church of Misericordia in Esposende, Portugal.

P_i	BP							UEGPT					FM					EPP			
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}	P_{21}
C_i	D	C	C	A	C	C	D	E	D	A	C	E	E	E	E	C	B	E	A	E	D
G_i	$G_1 = 75 * 0.35 = 26.25$							$G_2 = 100 * 0.2 = 20$					$G_3 = 100 * 0.3 = 30$					$G_4 = 100 * 0.15 = 15$			
D_V	$26.25 + 20 + 30 + 15 = 91.25 \therefore Heavy\ Level\ of\ Damage$																				

Figure 1: (a) Main Altar; (b) Exterior View; (c) Extension cords behind the main altar; (d) Storage room.

The second case is the 14th century Museum of Carmo in Lisbon, Portugal (38°42'43.5"N 9°08'25.4"W). The BP group was ranked as D, given that, in P_5, $r < 1$ and $nl \leq 2$. P_3 was graded as C since the largest compartment has approximately 190 m². P_1 and P_7 were graded as B due to the current use of the building (being a museum 80% with non-combustible material leads to a fire load of 500 MJ/m²) and the existence of vegetation 5-30m away from non-combustible materials, respectively. The other parameters of BP were graded as A, due to the non-combustible materials of the walls and the type of adjacent buildings (P_2 and P_4), and the good level of conservation of the few combustible materials in the structure (P_6). In terms of UEGPT, the building was graded as B, given that utilities are in good condition, the technical room is in the exterior but near the administrative zones, there is a CCTV system (Figure 2b) and the building is in a moderate criminal area. FM is graded as C since there is a fire suppression system (Figure 2a), an alarm and detection system (Figure 2b), a passive smoke control system (atrium), water supply and the firefighters are less than 10min away. Even though P_{20} leads to

a Class D (travel d <20 m and w<3), it is upgraded to B due to the integration of AS1 and SC3. EPP is graded as C since there are some measures of emergency preparedness but no emergency plan, given that the elevation is lower than 7 m and that there are signage and emergency lights, (see Figures 2c and 2d). The summary of the parameters is shown in Table 8 and Figure 3b, leading to a final damage level of 53.75 (medium damage).

Table 8: Fire Risk Assessment of Museum of Carmo Convent in Lisbon, Portugal.

P_i	BP							UEGPT					FM					EPP			
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}	P_{21}
C_i	B	A	C	A	D	A	B	A	A	A	B	B	A	A	C	A	A	C	A	B	A
G_i	$G_1 = 75 * 0.35 = 26.25$							$G_2 = 25 * 0.2 = 5$					$G_3 = 50 * 0.3 = 15$					$G_4 = 50 * 0.15 = 7.5$			
D_V	$26.25 + 5 + 15 + 7.5 = 53.75 \therefore Medium\ Level\ of\ Damage$																				

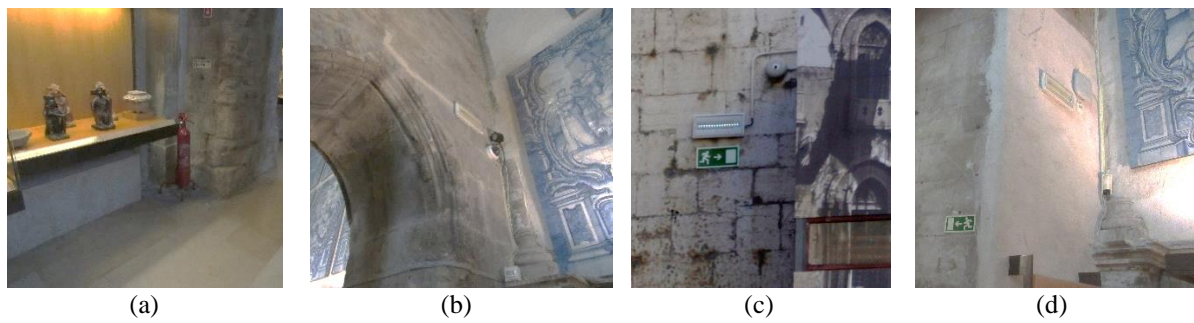(a)   (b)   (c)   (d)

Figure 2: (a) Suppression System; (b) CCTV; (c) Alarms system; (d) Signage.
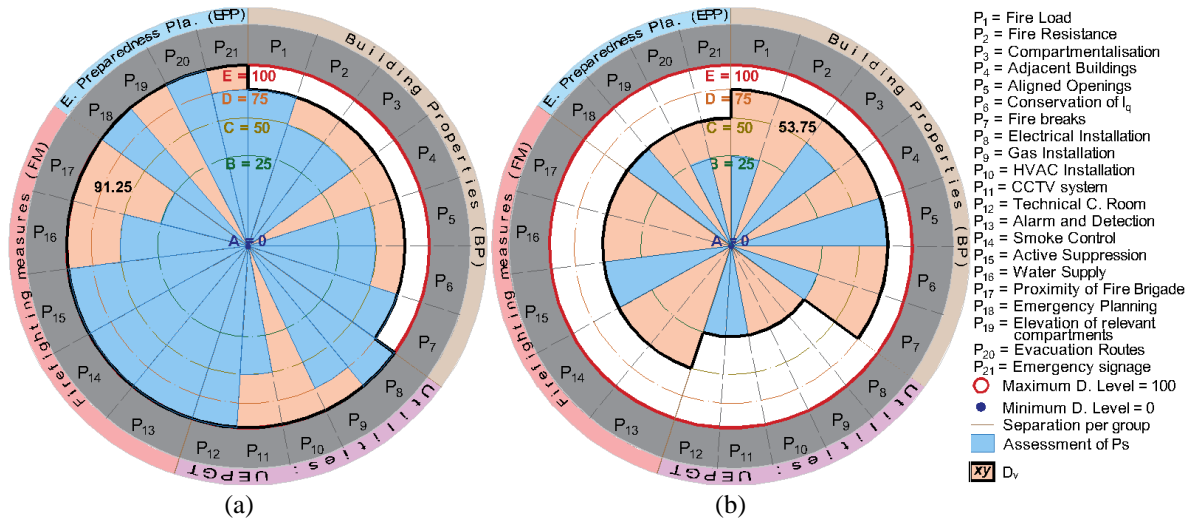

(a)   (b)

Figure 3: Fire index assessment (a) 16th Church of Misericordia; (b) 14th century Museum of Carmo.

4 CONCLUSIONS

Given the diversity and specificity of cultural heritage assets, simple approaches are required to analyse their fire safety and establish their risk mitigation needs. In this context, a simplified fire damage index dedicated to assessing the expected damage impact due to fires in immovable cultural heritage assets is proposed. The proposed index involves a weighted multi-parameter

evaluation that can be correlated with the level of damage that the cultural heritage asset (including its contents) is expected to suffer under a fire. The fire index was applied to two case studies in Portugal to illustrate the flexibility of its applicability.

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