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Assessment and Mitigation of the Fire Vulnerability and Risk in the Historic City Centre of Aveiro, Portugal

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Abstract: Identifying fire risk in urban centres is instrumental for supporting informed decision-making and outlining efficient vulnerability mitigation strategies. Historic centres are particularly complex in this regard due to the high density of combustible materials in these areas, the favourable fire propagation conditions between buildings, and the complex urban morphology, which makes the evacuation of inhabitants difficult in case of a fire emergency. Recent safety regulations tend not to be fully applicable to historic city centres, where the specificities of the buildings, together with the need to safeguard their heritage value, make the rules for new buildings incompatible. For that reason, an adaptation of current evaluation methods is required to assure the safety of these places. The present paper aims to contribute to this topic by presenting and discussing the results obtained from the application of a simplified fire risk assessment methodology to a representative part of the historic city centre of Aveiro, Portugal. Data were collected through fieldwork building inspections and the results were mapped using a Geographic Information System tool. The study reveals that around 63% of the assessed buildings have a level of fire risk greater than the level of risk which is acceptable for buildings with this type of use and value. Based on the work developed, different mitigation strategies are suggested and compared. Finally, the results obtained in this work are compared with results published for historic urban areas with similar characteristics.

Keywords: fire risk; risk assessment; urban risk; historic city centres; fire safety

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1. Introduction

Due to their material and morphological characteristics, traditional buildings are not usually prepared for current comfort and safety standards [1–4]. Fire is the most significant potential hazard in urban areas. Although the safeguarding of occupants' lives is certainly the most important point, the safeguarding of the building itself is also very relevant, since most of these buildings have heritage significance and value. This is, however, a very challenging task, not only due to the material and construction characteristics of these buildings but also due to the significant amount of fire loads involved, such as wooden ceilings and floors, textiles, and paintings, and oftentimes, the impossibility of installing fire protection devices in these buildings, such as sprinklers or smoke detectors [5].

These issues, together with a lack of adequate maintenance practices, have been responsible for the loss of buildings of inestimable value, such as the Notre Dame Cathedral in France [6] or the National Museum in Brazil [7,8]. With lesser patrimonial value, but potentially more significant consequences in terms of human losses, buildings located in Historic City centres do not easily comply with the generalities of current fire safety requirements, as those in the Portuguese Code [9], it thus being necessary to evaluate each case separately and accept conditions that, in normal circumstances, would be inadequate, such as narrow emergency paths and more combustible construction materials. This situation, alongside difficult firefighting settings, and favourable propagation conditions due to the proximity of buildings, poses a significant fire risk to these areas.

The number of urban fires has grown worldwide in recent years, particularly in Portugal [10], where areas of high fire risk are relatively well identified. Among a number of other historic areas, some of them already well-studied and characterised (such as the historic urban areas of Lisbon and Oporto), is the historic city centre of Aveiro, for which the level of knowledge regarding fire risk and safety is very limited, despite its high heritage and socio-cultural value [11]. Some studies have been conducted around the world [12–16] and have yielded very interesting results about how alternative methodologies work and how they can help historic sites with respect to fire risk. In addition, these methods have been significant in confirming the ANEQP [11] risk maps and specifying which areas are more likely to be affected, as well as determining the state of the buildings in those areas.

In Portugal, the regulations regarding the building fires prevention [9,17] was until 2019 applicable to new and existing buildings, prescribing for example minimal dimensions of evacuation paths, ventilation, and materials. This fact made the use of the rules and the preservation of heritage building very difficult. In 2019, identifying heritage buildings as particular cases, the "Decreto-Lei no. 95/2019" was implemented [18], allowing the exemption of some requirements since they were justified and analysed by the governmental commission. In sequence, the ARICA methodology developed by The Civil Engineering National Laboratory (LNEC) was approved as a legal tool to help engineers to justify their exemption choices regarding projects.

From this perspective, it is considered that the fundamental importance of the preservation of historic sites is to give the authorities precise information about their vulnerabilities. Based on the background described above, this work aimed to assess the fire risk of a part of the historic city centre of Aveiro through the application of a simplified fire risk assessment approach, which has already been applied in the evaluation of some historic urban areas in Portugal; see [16]. As comprehensively presented and discussed herein, this work involved extensive fieldwork to collect data about the specific characteristics of the buildings included in the study area, which were then used to get a fire risk index (FRI) for each building. These individual results were subsequently mapped using a Geographic Information System (GIS) tool, and the buildings identified as most critical were analysed with a view to suggesting possible risk mitigation strategies.

2. Methodological Framework

As mentioned above, the first step of this research involved the delimitation of the study area, which should be simultaneously wide enough to be representative of the whole building stock of the historic city centre of Aveiro, but still a reasonable size considering the amount of time and human resources allocated to the fieldwork. Once the data collection stage was finished, individual fire risk indices were calculated, integrated, and mapped using a GIS tool. Each one of these steps, from the identification of the study area and the description of the data gathering procedure to the explanation of the simplified fire risk assessment methodology used in this work, is reported in the following subsections.

2.1. Study Area and Field Survey

As a small medieval city, Aveiro grew inside its walls for defence against external invasions. Later, with the end of territorial disputes, the city started expanding beyond the walls. In the next centuries, due to the main source of local income being salt extraction, the city faced growth in the direction of the Ria de Aveiro lagoon, which provided salt water and agricultural organic fertiliser [19], as well as acting as a delimiter throughout the flooded areas near the city.

The expansion of the urbanisation process was started in the mid-16th century and, by the 19th century, it had already consolidated numerous buildings [20]. As a result of this growth, the area of the "Praça do Peixe" was created, surrounded by canals, and mainly composed of residential buildings and small businesses.

Good quality stone for construction is scarce in this region due to its geomorphologic characteristics and proximity to the sea. Because of this, only the most important buildings, such as churches, governmental buildings, or those belonging to the wealthiest families, were built with stone coming from other regions. Ordinary buildings, on the other hand, were typically built using adobe and timber [21,22] as the main construction materials, with ceramic tiles covering the façades [23].

Combining the lower values usually assigned to traditional buildings and the absence of maintenance, as well as the noncompliance of the buildings with applicable standards (and, later, touristic pressure [24]), led to the substitution or conversion of several buildings. With the spread of reinforced concrete structures associated with a more efficient construction, the mixing of reinforced concrete structures with traditional masonry and timber elements started to appear and, in other cases, total replacement by new reinforced concrete structures. This created a variety of different building typologies in the area.

Today, the area that shelters bars, hotels and residences is now one of the busiest and central zones of the city, gathering a great number of old and heritage buildings together. As a place conditioned by the morphology of its buildings and streets, resulting from its growth (Figure 1), the area is considered a key zone for applying alternative methodologies to the ones applied for the evaluation of new buildings.

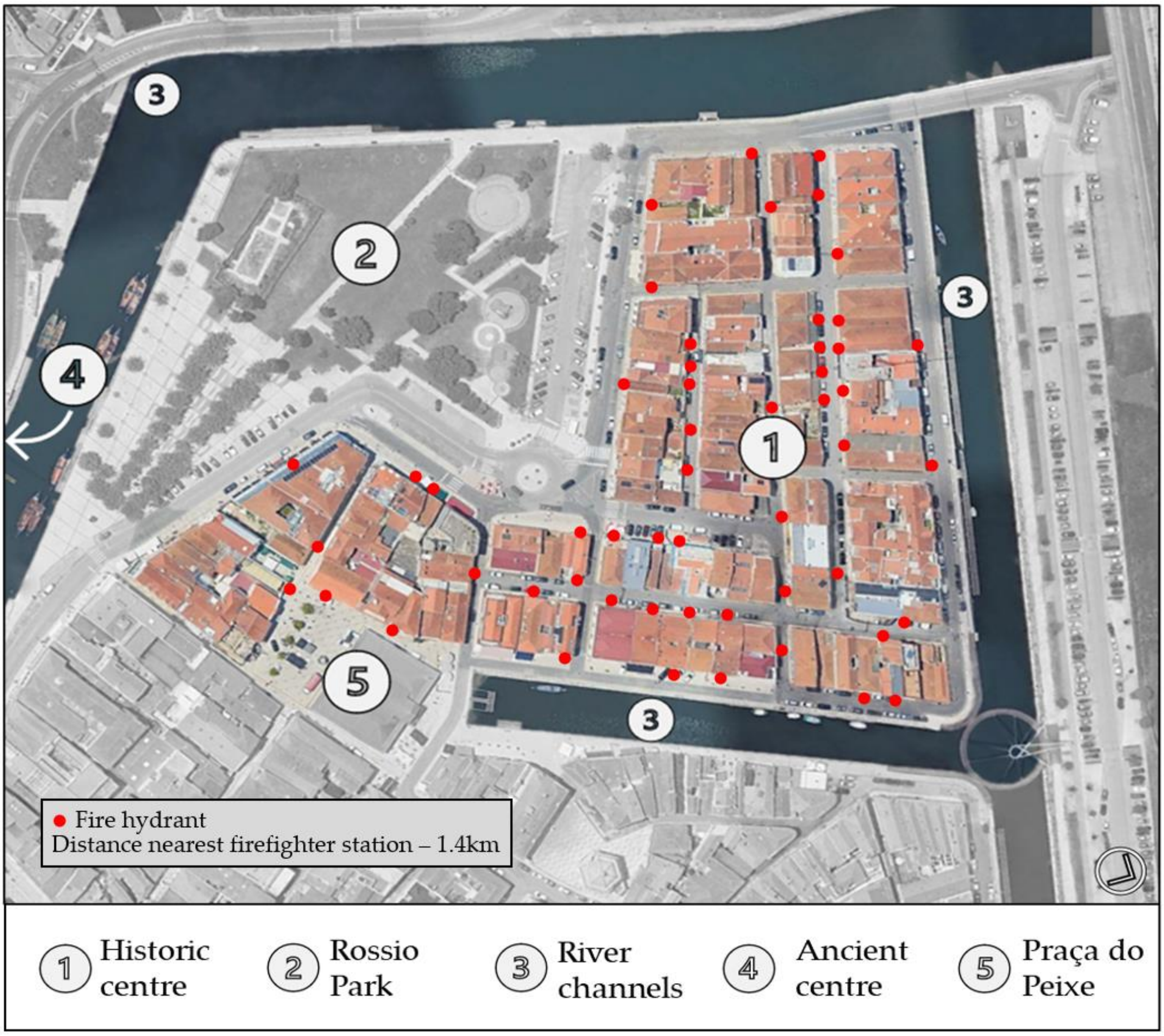

Figure 1. The historic city centre of Aveiro—Study area.

Based on the data acquired and conditioned by the great heritage value that highlights the local history and culture, a zone covering all the most recurrent building typologies in use was defined. The borders created by the canals were used as a divisor of the area (Figure 1). The total number of buildings placed in the zone was codified and catalogued after definition; the application of this work was directed through visual inspection of the group of facades and the collection of relevant information.

Several fire hydrants can be identified in the study area (Figure 1); however, it should be noticed that they are mostly located on the façade walls of the oldest buildings without periodical maintenance. In this sense, it could not confirm the reliability of these hydrants (posteriorly considered in the method as low reliability), exposing the probability that most of them may not work properly.

In total, the study area encompasses 153 buildings divided across 16 blocks. A significant percentage of these buildings (about 70%) have a residential or a mixed residential/commercial use. The remaining buildings have commercial, industrial, or cultural uses, mainly linked to the tourism industry (Figure 2). There were also three buildings undergoing major renovations at the time of the survey, which were left out of this analysis since the building works imply that they will comply with current fire safety requirements.

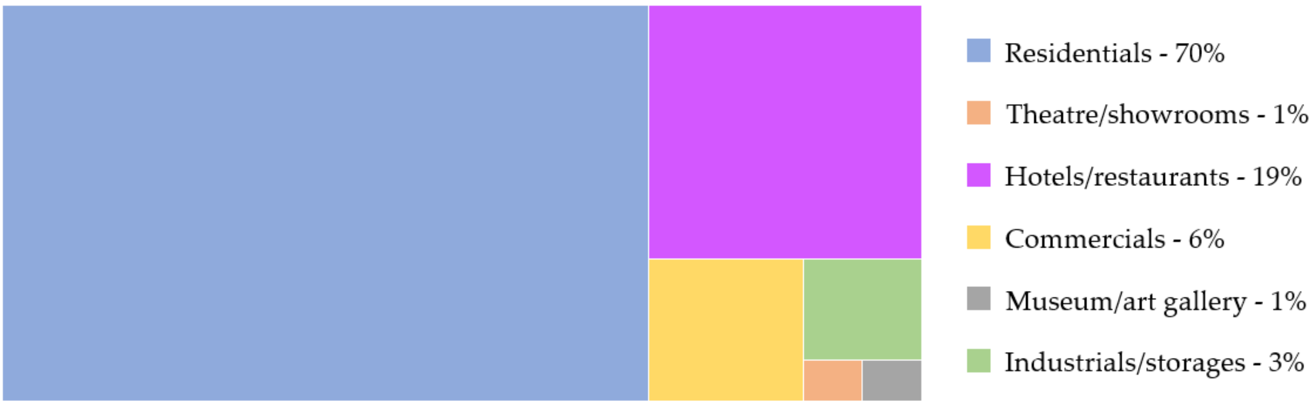

Figure 2. Distribution of the buildings regarding their type of use.

It is worth adding that 33 out of the 150 buildings included in this study (about 22%) were unoccupied or in a state of abandonment, which is a relevant aspect from a fire safety point of view. Another important fire risk parameter is related to the height and the number of floors of the buildings: in this case, it was found that 18% of the buildings considered in this work are 1-storey buildings, 34% are 2-storey buildings, and 41% are 3-storey buildings. The tallest buildings, representing 7% of the building stock across the study area, have 4-storeys.

2.2. Description of the Fire Risk Assessment Method

The fire risk assessment methods for buildings and public spaces result from the compilation of data related to the built environment, construction elements, surrounding conditions and the capacity of warning and fire extinguishing capacity. It is statistically weighted through the importance of each of the items considered.

Aiming to adapt and simplify the regulations for new buildings by the specificities of different construction typologies, exemplified by Gholitabar et al. [24], some methods developed for existing buildings stand out for their applicability and have been used by several research teams to validate the parameters and assess the risk to historic centres. In Portugal alone, some of these methods have been successfully applied to assess fire risk in several cities, including Guimarães [13,25], Coimbra [14], Castelo Branco et al. [15], Seixal [16,26] and Oporto [27]. These works not only allowed the consolidation of several risk assessment methodologies, making them more compatible and adjusted to the specificities of the Portuguese building stock, but they also generated significant amounts of data regarding the fire safety of these areas.

Most of the methods correlate data on the morphological characteristics of the buildings with information related to the existence and level of operationality of fire protection and firefighting equipment, such as extinguishers, smoke alarms and hydrants, differing essentially in the scope and scale of the evaluation. The ARICA method, for example, focuses more on the expeditious evaluation of the general aspects that most influence the ignition, propagation, combat, and evacuation processes, whereas the Gretener and FRAME methods [15] comprehensively address the internal characteristics of the buildings.

Because it was more adequate for the data set (mainly collected in an expeditious way), in visually evaluating the content of the area, the ARICA method (mentioned in the introduction section) was applied throughout the Fire Risk Index (FRI) simplification for the definition of fire risk in the urban context of the neighbourhood. This method, which is explained in more detail in [12], is based on the collection of information about the buildings and public space by correlating two large groups of data (Table 1): data related to the risk resulting from the characteristics of the building itself, which are used to calculate the Global Risk Factor (GRF), and data related to all the aspects affecting firefighting capacity, which are used to work out the Global Efficiency Factor (GEF).

Table 1. Determination of the fire risk index (FRI) global factors.

Global Risk Factor (GRF)			**Global Efficiency Factor (GEF)**
Sub-Factors (SF)			
SF_I (Ignition)	SF_P (Propagation)	SF_E (Evacuation)	SF_C (Combat)
Partial Factors (PF)			
PF_{A1} (Building conservation) PF_{A2} (Conditions of electric installations) PF_{A3} (Conditions of gas installations) PF_{A4} (Fire load nature)	PF_{B1} (Distance between parallel openings) PF_{B2} (Safety teams in the building) PF_{B3} (Existence of fire alarm) PF_{B4} (Intern compartmentalisation) PF_{B5} (Fire loads)	PF_{C1} (Conditions of the evacuation routes) PF_{C2} (Building properties) PF_{C3} (Correction factor for evacuation)	PF_{D1} (Conditions of external firefighting equipment) PF_{D2} (Conditions of internal firefighting equipment) PF_{D3} (Preparation of safety teams in the building)

The diagram shown in Figure 3 highlights the link between the data collected on-site as components of the partial factors (PF), which are converted into sub-factors (SF) and applied to the fire risk FRI methodology. The four SF groups are then weighted by their importance in the overall risk composition, with SF_I (Ignition) being increased by 20%, SF_p (Propagation) increased by 10%, and SF_E and SF_C (Evacuation and Combat, respectively) not being increased, according to the method.

The result of the weighted average of the sub-factors results in the Global Risk (GR) (Figure 3), and this result needs to be corrected according to the height and the use typology of the building through the Reference Risk (RR) equations. The product of this process is the Global Fire Risk (GFR), presented in Equation (1), which is a dimensionless factor which measures how far the GR factor is from the RR factor and makes it possible to quantitatively determine whether buildings are suitable for habitation or not:

$$GFR = \frac{\frac{(1.2 \times SF_I + 1.1 \times SF_P + SF_E + SF_C)}{4}}{RR} \quad (1)$$

Divided by RR, the GFR must be less than 1.00, which means the same as the maximum acceptable reference risk for that specific building's typology. When this condition is not met, vulnerability mitigation strategies should, potentially, be put in place to reduce the fire risk of the building. This is addressed in more detail in Section 4 of this manuscript.

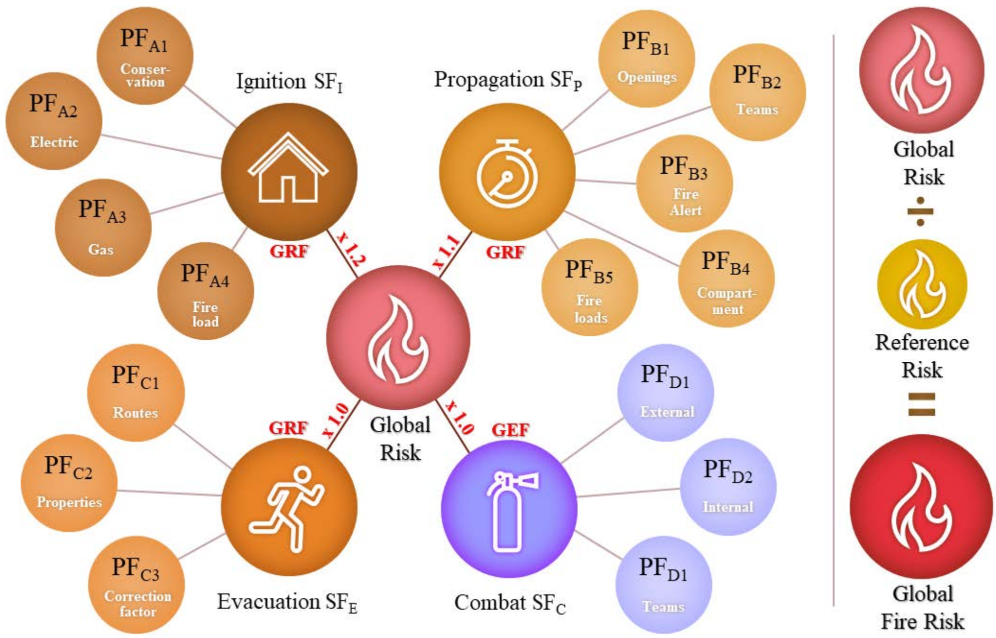

Figure 3. Application diagram of the Fire Risk Index methodology.

For the sake of a better understanding and mapping of the results, the GFR value was divided into four categories of increasing risk: 1. Low, 2. Medium, 3. High, and 4. Very High (Table 2). These four categories were derived and adapted from the ARICA methodology which determines that the risk is 'just acceptable' when GFR is lower than 1.0 and 'not acceptable' when GFR is greater than 1.0. Thus, in this case, it can be considered that, until the medium category, the building has an acceptable fire risk and, up to this, it is important to develop some actions to mitigate the risk [16].

Table 2. Classifications of GFR.

Value of GFR	Classification
$GFR \leq 0.9$	Low Risk
$0.9 > GFR \geq 1.0$	Medium Risk
$1.0 > GFR \geq 1.1$	High Risk
$GFR > 1.1$	Very High Risk

With the production of quantitative data, there is the possibility of punctually finding the aggravating factors of the risk, thus enabling decision-making and appropriate actions to be taken to mitigate the determining factors and contributing more succinctly to the overall improvement of the buildings and the area.

3. Fire Risk in the Historic City Centre of Aveiro

Based on the FRI method, a visual survey was carried out to acquire the required information. The site data collection was performed in two days combining facade observation and randomly getting complementary information with residents. Jointly with the authors, a group of 10 master students were evolved to perform the collection of the information. Once the surveys were filled, the site collected data was complemented with online data sources, such as Google Maps and Google Earth, and provided by the municipality.

The gathered information was allocated in a spreadsheet which performs the necessary application of the equations and classification establishing, subsequently, the method results. All the existing buildings were analysed through the survey and the method was applied to each of them. Based on the results, the buildings were divided into four categories, according to the Global Fire Risk and typology of use (Table 3). These data allow the use of the GIS system to visualise the fire risk and intuitively assess the most compromised areas and buildings.

Table 3. Global Fire Risk per category/typology of use.

Typology of Use	Global Fire Risk Categorisation				Total Σ (Use)
	Low	Medium	High	Very High	
Residential	1.7%	21.0%	30.6%	16.1%	69.4%
Theatre/auditorium	0.0%	0.6%	0.0%	0.0%	0.6%
Hotel/restaurant	0.6%	11.3%	5.9%	0.8%	18.6%
Commercial	0.0%	1.3%	4.7%	0.7%	6.7%
Museum/art gallery	0.0%	0.6%	0.0%	0.0%	0.6%
Industrial/storage	0.0%	0.0%	0.0%	4.2%	4.2%
Total Σ (Categories)	2.3%	34.8%	41.2%	21.8%	100.0%

According to Table 3, only 37% of the buildings present a fire risk classification which is lower than the maximum risk acceptable, according to the FRI methodology; this result is also shown in Figure 4. When it focuses on residential use, which represents more than two-thirds of the building typologies, this number decreases to less than 23%, and this high number of residential buildings at fire risk is recurrent and has already been highlighted by [28]. It is important to note that a great part of the buildings is used over long periods of time, so they need special attention when it comes to people's permanent exposure to the fire risk. Compared to the historic city centre of Guimarães [25], with similar conditions using a similar methodology, a lower risk was observed; just 6% of the buildings showed a low-medium risk of fire. The main reason for the differences found may be related, with the narrow streets and characteristics based on building evacuation directly pointing to the reason for that difference.

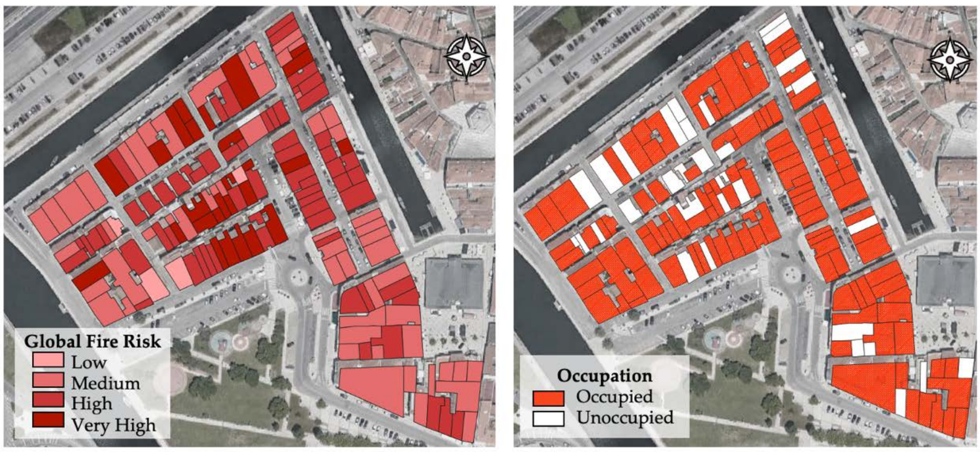

Figure 4. Global Risk Factor and unoccupied buildings, respectively.

On the other hand, besides residential buildings, the historic city centre of Aveiro presents better results in the other typologies; in this case, low-medium fire risk corresponds to half of the constructions and, when it comes to high frequented places (excluding industrial/storage), this number increases a bit more. This situation is mainly justified by the national regulations for building uses with public concentration, but a considerable number of buildings are still exposed to greater risks than what is deemed to be acceptable (Figure 4).

As a result of the high exposure to fire risk, the probability of urban fires remains very high, as observed by the Portuguese National Agency in the Aveiro region [10]. Moreover, the problem is aggravated by the uninhabited buildings (Figure 4), which make a special contribution to the global risk, justified by late warnings (after the start of a fire). It is noticeable that about 22% of the buildings are currently in that state and the pattern of use is repeated by 74% of those characterised as being residential. In the case of Seixal and Guimarães, the empty properties were also identified, and it can be seen as a recurring reality in historic city centres [16,24].

In Figure 4, in the central blocks of the area, there is a higher concentration of buildings containing a high fire risk. This effect is explained by the higher number of residential buildings. As already observed in Table 3, the category of residential typology is related to the increase in the fire risk; for example, in the Very High Fire Risk category, the residential buildings represent 70% of the buildings in the category.

Fire Risk per Sub-Factor

Separately evaluating the sub-factors helps define and design the mitigation solutions.

These different hazard sources have already been identified by different authors [25,29] and largely exemplified in the case of the historic city centre of Coimbra [14]. According to the FRI methodology, the most important ones are related to the beginning of the fire (SF_I), and its spreading (SF_P) (increased factors of 20% and 10%, respectively); such a case is explained by the city morphology which promotes a bigger probability of global risk.

Figure 5 presents the four sub-factors individually, showing some heterogenicity between the buildings. As mentioned before, the first two sub-factors are the most important, particularly in the case of SF_P, where the fire exposure directly affects the neighbouring set. In this group, the risk is aggravated, mainly due to the lack of fire alarms and detection systems, as well as the nature of traditional buildings that do not present very efficient cut-fire compartmentation.

Figure 5. Sub-factors of fire risk, SF_I, SF_P, SF_E, and SF_C, respectively.

Still referring to the beginning of the fire, by analysing SF_I in Figure 5, it is possible to infer that the sub-factor related to the fire ignition is very heterogeneous, and it is the one that most contributes to the GFR. In this case, old infrastructure, like exposed gas pipes and unprotected electric installations, is a major influence and is increased by generally poor maintenance or conservation. Hence, this confirms that higher risk is usually related to a lack of conservation or maintenance and failure to renew existing infrastructure.

When evaluating the last two sub-factors (SF_E and SF_C), buildings present more homogeneous indicators. In the SF_E case, there is notably higher risk located in the middle part of the area that corresponds to buildings with two or three floors, especially those where their exits are partly blocked, or they have narrow stairs and doors. These are important issues when there is a fire because people need to have a fast and easy evacuation route and those with reduced mobility will have even greater difficulties.

Reviewing the last sub-factor, most of the buildings have a low combat sub-factor, and more than 85% of the buildings (around 130 buildings) have a SFc value lower than 1.81 and 25% (37 buildings) lower than 1.30, by combining the preparation of the firefighting crews and the fire extinguishing capacity of the buildings, considering the water availability and accessibility of the external help. However, an area with higher risk is identified close to the corner of the river, which is mainly due to the lack of firefighting facilities in the area.

Considering all the values, the high deviation of SF_I and SF_P, compared to SF_E and SF_C, concords with the statement that the first two display more heterogeneous behaviour. This situation is relevant from the perspective that the buildings with high fire risk also expose the neighbouring buildings.

4. Mitigation Strategies

With the aim of enhancing some characteristics that have a strong contribution to the severity of the fire risk, as evidenced in the previous section, in 63% of the cases, the GFR is deemed to be acceptable; therefore, some preventive solutions to help the mitigation and increase security in the urban core are proposed.

The selected method for developing the mitigation strategies for the area being studied was to look at each sub-factor and assess its weight in the contribution to the SF risk in the group. Although, considering that each individual solution can be hard to execute, depending on the engagement of the residents in the area, the first option is to develop public policies and facilities to offer a reasonable security improvement to the site.

4.1. Public Mitigation Measures with Strong Impact

During the visual inspection, the lack of reliability of urban fire hydrants (or even their absence from some streets) was indicated as one of the problems with a relatively easy solution. The municipality can elaborate a maintenance plan for the existing fire hydrants and proceed with the installation of the missing ones, to ensure water availability for the firefighters, in case of an emergency [16].

By adjusting the Partial Factor related to water availability in case of an emergency, which is placed in the last sub-factor (Global Efficiency Factor–Combat (SF_C)), a relevant increase was found in the number of buildings with a fire risk that was less than acceptable, increasing from 37% to 54% with the interventions.

In addition, fire alarms could be distributed (with buttons accessible to the inhabitants). This solution has already been proposed by other studies, showing effectiveness in the reduction of evacuation time [4], once the system is relatively simple and economically affordable to introduce into the buildings, facilitating an alert for the whole neighbourhood, including the firefighters. Installing this type of system is also important from a social point of view, as several houses are used by older people who may have more difficulties warning others about risky situations, as well as evacuating from the building after a fire has been initiated.

Action in this Partial Factor is particularly helpful seeing as it relates to the Global Risk Factor–Propagation (SF_P) and Evacuation (SF_E) and, in this way, it has an important influence on the GFR.

In addition, assuming that Package 1 of mitigation measures is implemented, an important decrease in the absolute risk value can be observed, of around 67% of the total building stock analysed. This presents a low/medium risk and exposure to the 'very high risk' category decreases to less than 5% of the building stock (Table 4).

Table 4. Global Fire Risk per category/typology of use—After Package 1 of Mitigation Measures.

Typology of Use	Global Fire Risk Categorisation			
	Low	**Medium**	**High**	**Very High**
Residential	3.0%	48.2%	17.5%	0.8%
Theatre/auditorium	0.0%	0.6%	0.0%	0.0%
Hotels/restaurants	0.6%	16.5%	1.4%	0.8%
Commercial	0.0%	2.6%	3.5%	0.8%
Museum/art gallery	0.0%	0.6%	0.0%	0.0%
Industrial/storage	0.0%	0.0%	1.4%	2.3%
Total Σ (Categories)	3.6%	63.8%	28.0%	4.7%

After the application of this first package of mitigation measures, which are mainly promoted by the public authorities, a positive effect was observed on the global risk.

4.2. Individual Mitigation Measures with Strong Impact

In a second approach, Package 2 of mitigation measures was considered, introduced by stimulating the population to make adaptations to their buildings, specifically in terms of electric and gas installations. In this case, public authorities are coadjutants in the measures, promoting their implementation through tax policies, aiming to provide incentives for people upgrading buildings to safer security requirements.

Considering the lack of electrical safety systems in old installations and the frequent neglect of cables and other components for electrical devices, which increases the exposure of fire starting, this situation is synthesised from several studies by the assessing workplace facilities [30]. Consequently, the alteration of those systems is considered for this package. The Partial Factor related to the reliability of electric installations, which is placed in the first Sub-factor (Global Risk Factor–Ignition (SFI)), was recalculated, and it was found that a reduction in the High and Very High-risk groups placed about 72% of the buildings into 'acceptable' risk.

Considering that gas networks are available in the street areas under study, the mitigation package also proposes the linking of all the buildings to the public distribution network, avoiding individual gas bottles inside houses, often with deficient installation. However, in other cases, there may be a different approach; for example, in Oporto [27], it was decided to keep gas bottles, in order to minimise the financial impact. Table 5 shows the improvement precisely in the residential group after this strategy, placing more than 90% in the Low/Medium group following the FRI method. Apart from the residential improvement, this measure did not have any other expressive effect.

4.3. Low Effort Strategies with Minor Impact

Lastly, Package 3 of mitigation measures would not take a significant effort to be implemented but would have a lower impact. Commercial places should follow the national law regarding fire safety, and public authorities must inspect those places to make sure that they are operating within the rules. This action tends to increase the safety of buildings, mainly commercial ones; however, they are frequently not adequate because of a lack of inspections or the inattention of owners, and, consequently, they only have a minor impact on the real safety of the area.

Table 5. Global Fire Risk per category/typology of use—After Package 2 of Mitigation Measures.

Typology of Use	Global Fire Risk Categorisation			
	Low	**Medium**	**High**	**Very High**
Residential	4.2%	55.0%	9.2%	0.0%
Theatre/auditorium	0.0%	0.7%	0.0%	0.0%
Hotels/restaurants	0.6%	16.7%	1.4%	0.8%
Commercial	0.0%	4.0%	2.2%	0.8%
Museum/art gallery	0.0%	0.6%	0.0%	0.0%
Industrial/storage	0.0%	0.0%	1.4%	2.3%
Total Σ (Categories)	4.8%	77.1%	14.2%	3.9%

The simulated impact of rigorous inspections, in accordance with the numbers of security teams, firefighters and detection, would promote better Global Fire Risk. These changes would promote a reduction of 2.3% of the Very High-risk buildings and 1.4% of the High-risk ones, as previously referred to in non-residential cases.

Another measure with some impact comes from the provision of fire extinguishers for some buildings, especially those with High/Very High risk. Assuming that the non-residential buildings were already improved by the previous step, only the residential ones with High/Very High risk would receive the equipment, resulting in a movement of about 1.4% from the High-risk group to the Medium Risk one (Table 6). This policy is also not considered a very adequate action because it involves other variables; for example, the inhabitant may not be able to use it or they may not provide proper care and maintenance of the equipment.

Table 6. Global Fire Risk per category/typology of use—After Package 3 of Mitigation Measures.

Typology of Use	Global Fire Risk Categorisation			
	Low	**Medium**	**High**	**Very High**
Residential	4.2%	57.3%	7.1%	0.0%
Theatre/auditorium	0.0%	0.7%	0.0%	0.0%
Hotels/restaurants	0.6%	17.5%	1.4%	0.0%
Commercial	0.0%	5.4%	1.5%	0.0%
Museum/art gallery	0.0%	0.6%	0.0%	0.0%
Industrial/storage	0.0%	0.7%	1.5%	1.6%
Total Σ (Categories)	4.9%	82.2%	11.4%	1.6%

After all the modifications of the factors, Table 6 shows that about 87% of the buildings are now between the acceptable values specified by the FRI methodology, placed in the Low/Medium group of risk. It is also possible to see that in only 1.6% of the cases (corresponding to two buildings) is the Global Fire Risk Very High; the use of these buildings is storage, and the intrinsic fire load promotes their risk.

The increment of buildings in the acceptable area is very significant.

Figure 6 shows that the group of Low/Medium risk (green area) had an important reaction to the first two adjustments: the third package only having minor impacts on the global scheme.

Even though High and Very High GFR are scattered in all the blocks, Figure 7 presents a bigger concentration of the more exposed buildings in the central zone of the study area. This effect is directly related to the fact that such buildings have bigger PF in the Evacuation Sub-factor. After the implementation of the three packages, the Evacuation Sub-factor was not widely changed due to the difficulty of implementing the measures, justifying the higher risk focus.

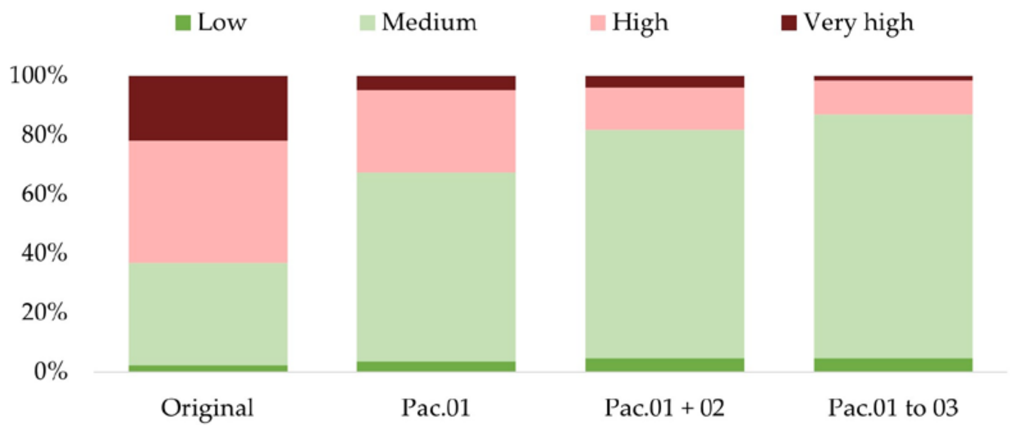

Figure 6. GFR classification at each adjustment stage.

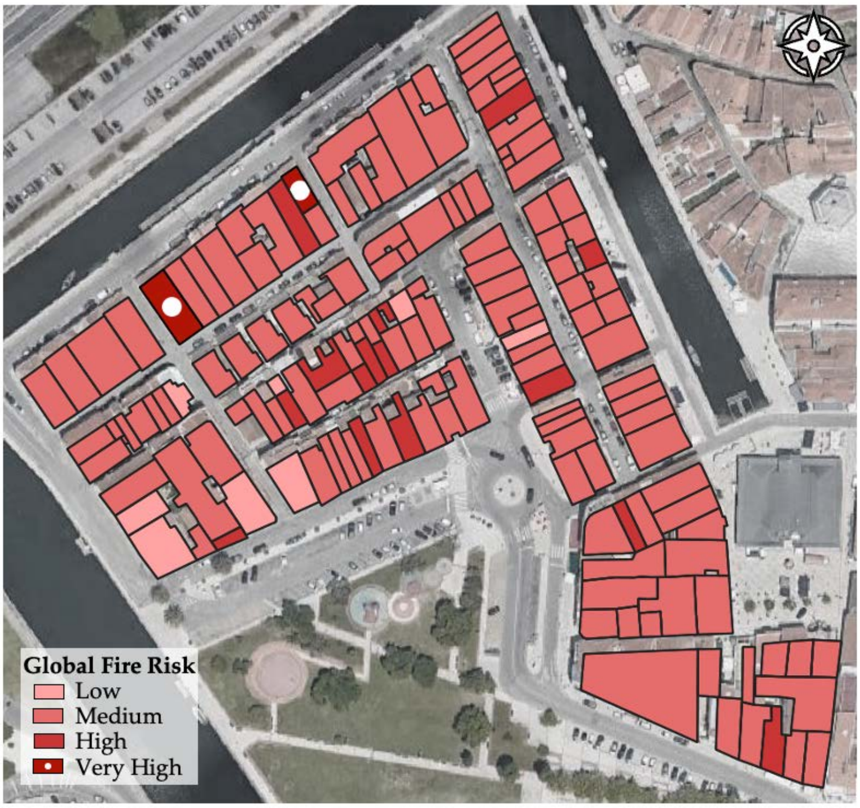

Figure 7. GRF neighbourhood map after all the adjustment packages.

With the aim of decreasing the fire risk, it might be important to implement further mitigation measures, such as enabling all the inhabitants as components of the fire teams at cultural sites, or proposing the complete rehabilitation of the buildings [31]. Those actions were not deemed to be completely effective in this case, as it was assumed that they are financially consuming or dependent on the acts of the inhabitants. Such actions would certainly decrease the risk even more than the ones chosen, but they were considered optional measures.

5. Conclusions

Historic sites, particularly the old historic city centres, need to be paid special attention regarding the application of rules and standards that are designed for new buildings. The relationship between the need to maintain traditional restrictions and the safety requirements imposed by codes for new buildings are usually mismatched. The historic city centre of Aveiro fits this case, and this justifies the option for a Fire Risk Index methodology to investigate the actual exposure of the area to fire risk and study measures to mitigate that risk.

After applying the method, some vulnerability was found as city centres show some similar patterns. As observed in other cases, the results of the method without any local intervention showed that, from a fire risk point of view, less than half of the buildings were considered safe, compared to the new ones. This number was even worse when it came to looking at residential occupation (long permanency), where about 75% of the buildings did not show an acceptable level of risk.

Using the collected data, some mitigation strategies were considered to understand each solution's impact on decreasing the fire risk in historic areas. The proposed changes were divided into three packages. The first package significantly reduced the fire risk, and the two subsequent packages promoted security growth, from 37% to 87% of the buildings now achieving acceptable values, according to the methodology. Some deeper modifications could be performed to increase the security of the site even more, but those would involve larger social and economic costs. Further studies aligned to other risk assessments might be performed.

Lastly, it is important to note that the application of a simplified method might exclude important data from the fire risk analysis and compromise the deeper results added to it. Other variables can be included to create a more complete panorama of the area. Having this in mind, the study contributes to a general overview and can be used as a first approach to critically needed interventions. Furthermore, the application of the method contributes to establishing and enlarging the fire risk assessment data of historic city centres.

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