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Fire risk assessment methods for historical buildings

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Abstract. Historical buildings refer to buildings located within conservation areas designated by local and international institutions or within traditional contexts, possessing significant architectural or historical value. These buildings represent the cultural and architectural heritage of humanity and serve as key symbols shaping the identities of societies. However, these valuable assets are exposed to both natural and human-induced threats. Among these, fires stand out as one of the most devastating events capable of destroying such buildings. Fires often cause not only significant material losses but also the loss of cultural heritage.The impact of fires on historical buildings is not limited to material losses. These buildings are often living witnesses of history, art, and culture. The destruction of historical buildings in fires harms the shared heritage of societies and humanity. Analyzing past fire incidents involving historical buildings reveals that these buildings, due to the lack of widespread fire engineering and inspection practices during their construction periods, are particularly vulnerable to fire because of their construction systems and material choices. Various Fire Risk Assessment (FRA) methods are used to evaluate the fire resistance of these buildings in their current state. However, historical buildings require a distinct assessment method due to their unique characteristics. In this context, the study analyzes existing FRA methods, discusses the factors that should be considered for risk assessment specific to historical buildings, and highlights the strengths and/or shortcomings of these methods in comparison to one another.

Keywords: Historical buildings; Fire; Risk analysis; Assessment method; Fire risk assessment.

1. Introduction

Fire can be simply defined as the rapid oxidation of a substance involving heat and light. In general, oxidation is the chemical combination of any substance with oxygen. Heat is also produced from this combination, but it is very difficult to measure because it is so small. Fire can usually only occur when three things are present: oxygen in some form, fuel (material) that will combine with the oxygen, and sufficient heat to sustain combustion. Removing any one of these three factors will result in the extinguishing of the fire. The classic "fire triangle" is a graphical symbolization of the known elements involved in the combustion process (Fig. 1). Opening the triangle by removing one factor will extinguish a growing fire, and preventing any one factor from joining the other two will prevent the fire from starting.

Some studies in the literature show that this chemical reaction cannot consist of only these three factors. According to Haessler (1974), a fourth factor, the "reaction chain", was determined and it is stated that this factor starts from the moment the combustion starts and even accelerates during the combustion. The reaction chain is formed by the disintegration and recombination of the molecules that make up a flammable material with the oxygen of the atmosphere. The investigation of this concept has led to the discovery of many extinguishing agents that are more effective than those that managed to open the triangle. Due to this discovery, the fire triangle can be turned into a three-dimensional pyramid known as the "fire tetrahedron" (Hasofer, Beck, & Bennetts, 2006) (Fig. 1). This difference in the literature does not eliminate all the old procedures that can be used in preventing fires, but it provides additional tools with which fires can be prevented or extinguished. This difference in the literature does not eliminate all old procedures that can be used to prevent fires, but it provides additional tools to prevent or extinguish fires. When disasters that occurred in buildings throughout history are examined, fire has always been one of the greatest threats to life (Hurley, et al., 2016). In the oldest times, fires occurred in the natural environment of forests and meadows, while today the greatest fire risk in the historical fabric is fires that occur on flammable materials in the built environment. The most important reason for this can be shown as the lack of architectural/engineering services required for fire safety of historical buildings as they are today and the lack of sufficient information about fire by users (the formation of fires and what can be done to prevent it, as explained above).

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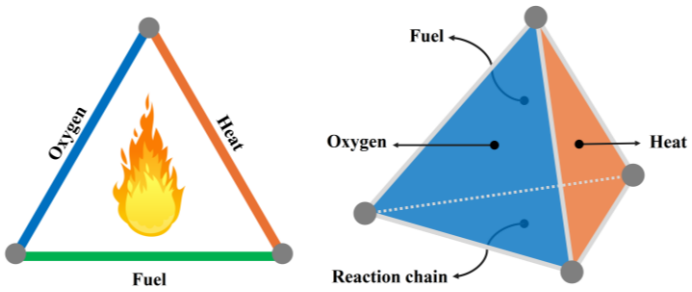


Fig. 1. Fire triangle and fire tetrahedron (Adapted from Hasofer et al. (2006))

In the first settlements built throughout history, buildings were generally small and single-story. This provided the residents with the opportunity to escape to a safe place. Since they were simple structures, lost property could be replaced relatively quickly. As civilizations became more organized and complex, settlements became larger. Buildings began to have upper floors, fires broke out, especially from the appliances used in kitchens and living rooms, and candles and gas lamps used for lighting purposes added to the fire risks, increasing the overall fire risk of the building. Throughout history, disasters such as the Great Fire of London in 1666 have caused great loss of property and life in such communities (Kıdd, 1995).

The best response to such disasters has been to learn from them. Some of the lessons learned over time include; development of building codes, consideration of compartment size (in terms of volume) in terms of fire resistance, awareness of the need for a consistent fire precaution package, importance of occupant response to fire and human behavior in a fire, etc. However, increased fire precautions in buildings have not ensured safety and fire disasters continue to occur even in seemingly safe buildings. Therefore, the way to deal with the stochastic (or random) nature of fire is probabilistic fire risk assessment (Ramachandran & Charters, 2011).

Historical buildings are vulnerable to fire due to the limited architectural/engineering services they receive and the inadequacy of the materials used in terms of fire resistance when the year of construction and the conditions of that year are taken into account. In this sense, conducting fire risk assessment on historical buildings is very important in transferring these buildings, which have symbolic value for society and are an important element of cultural sustainability, to future generations. The study focused on Fire Risk Assessment (FRA) methods accepted in the literature due to the sensitivity of historical buildings to fire.

1.1. Methodology

Within the scope of the study, the general classifications of FRA methods in the literature, the reasons for the emergence of these classifications and FRA methods specific to historical structures were investigated. As a result of these studies, the selected FRA methods were analyzed over the determined analysis headings. As a result of these analyses, evaluations and some inferences were made specifically for historical structures (Fig. 2).

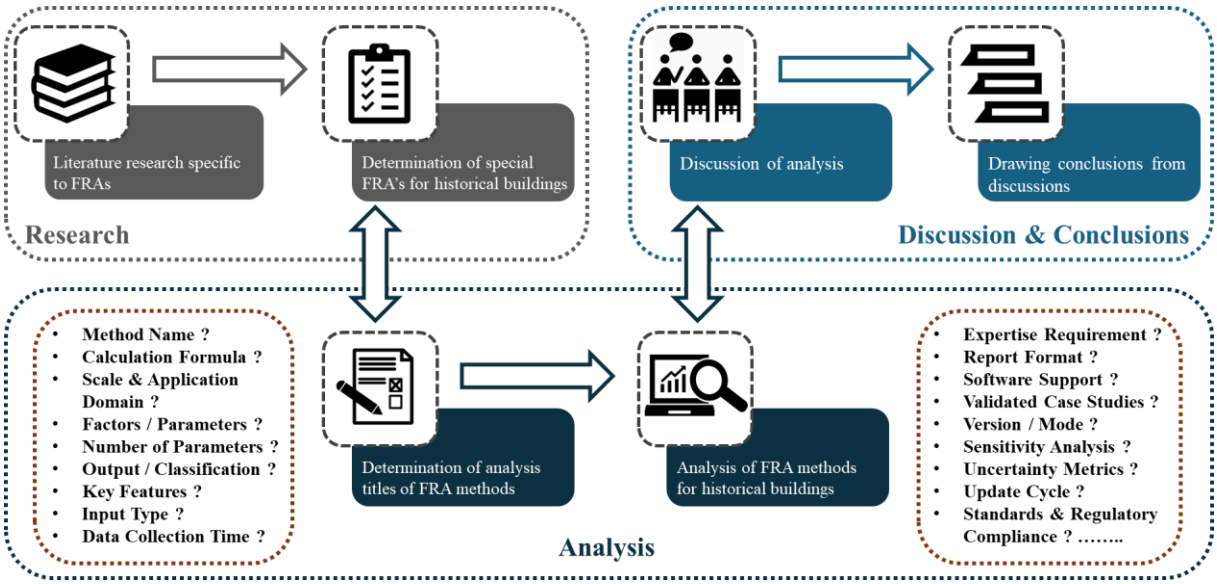


Fig. 2. Schematic description of the methodology of the study

2. Fire Risk Assessment (FRA) methods

Fire Risk Assessment (FRA) methods are a preventive tool for architects and engineers to evaluate fire risk, its possible consequences and the necessary safety measures. Risk prevention methods are the most practical tools in minimizing the consequences of fire, as they include some unpredictable factors such as human behavior and the response time of rescue services. Guerrazzi (2023)'s SFPE Fire Risk Assessment Guide defines Risk Assessment as "the process of generating information about acceptable risk levels and/or risk levels for an individual, group, society or the environment." As can be understood from their definitions, FRAs have a complex structure due to the fact that different factors serve a common purpose together. For this reason, there are many different classifications in the literature. These classifications are summarized below.

2.1. Classification of FRA methods

According to different sources, FRA methods can be classified in more than one way depending on the criteria chosen (Fig. 3). These classifications are not mutually exclusive, but they form a complex network where the same method can belong to several categories according to the criteria chosen (Iglesias, 2018). Not all methods can be classified into one of the above categories, and all categories are interrelated. In addition, sometimes the name of the category is a method itself (as in the case of checklists or indexing methods).

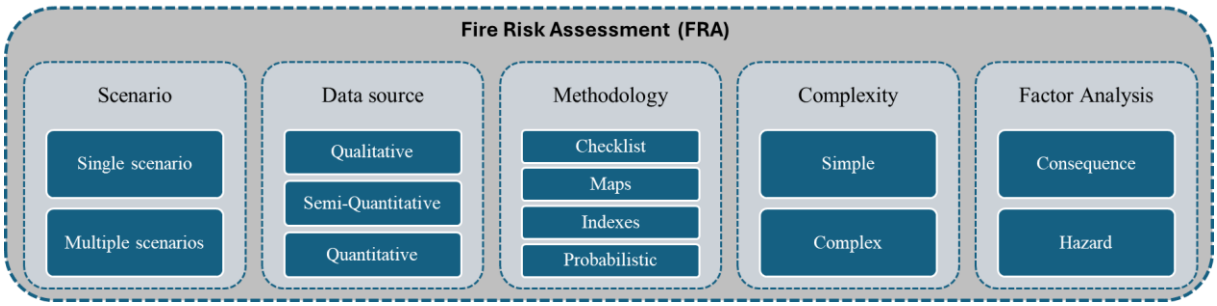


Fig. 3. Different types of classification of fire risk assessment methods (Adapted from Iglesias (2018)).

Among all the methods mentioned above, the most preferred classification is the one made through “Data source”. Within this classification, there are various different methods under the headings “Qualitative, Semi-Quantitative and Quantitative” (Fig. 4).

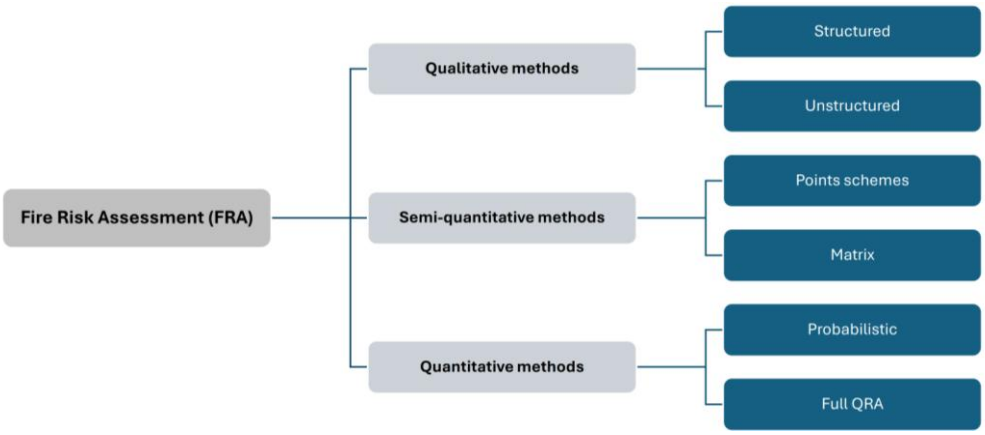


Fig. 4. Widely preferred classification of FRA methods (Adapted from Ramachandran & Charters (2011)).

Qualitative fire risk assessment is based on a subjective judgment not only of the probability of a fire hazard or fire scenario occurring, but also of the outcome of such a fire hazard or fire scenario. Qualitative fire risk assessment is often used to obtain a rapid assessment of potential fire risks in a building and to consider various fire protection measures to minimise these risks (Yung, 2008). Qualitative methods are based on identifying the factors that affect risk. These factors can be factors that affect the level of danger, such as the level of fire precautions aimed at reducing the hazard, such as flammable materials or fire detection. All of these factors are assessed against a set of benchmark values and a judgement is made as to whether the factor is higher, lower or about the same as the benchmark. All factors are then examined to assess how the assessed area compares to the benchmark values. Assessments under fire regulations for existing buildings usually fall into this category (Ramachandran & Charters, 2011).

Semi-Quantitative fire risk assessment methods give a numerical value to the risk level; however, this numerical value does not represent an exact risk value (Ramachandran & Charters, 2011).

The term quantitative fire risk assessment refers to an assessment that includes numerical quantities not only of the probability of a fire hazard or fire scenario occurring, but also of the consequences of that fire hazard or fire scenario. The numerical values of probability and consequence are multiplied to give each fire scenario a numerical fire risk value. By adding the risk values from all possible fire scenarios together, we can obtain an overall fire risk value. The overall fire risk value can be used to make comparisons with alternative or code-compliant fire safety designs (Yung, 2008).

3. Historical buildings and FRA

Historical buildings around the world are exempt from local and/or international building codes, relying on the experience of designated authorities to determine what is safe or what is an acceptable equivalent to a specific code requirement. In this sense, historic buildings suffer under codes that either completely ignore historical significance or impose strict safety requirements with minimal regard for culturally significant areas and materials. As a result, the historic character of a building can be damaged by the strict application of fire safety codes. At the same time, the current international perspective on fire safety objectives includes, in particular, the protection and preservation of life, property, mission, environment and cultural heritage (Watts Jr. & Kaplan, 2001).

Historic buildings present unique challenges for fire protection. Unlike most public and commercial buildings, a historic building exists as a work of architectural or historical significance or as a visual record. If the building is demolished, this function is eliminated. Creative solutions must be developed that meet fire and life safety objectives without compromising the historic building's historical or architectural significance. However, no statistics are available to determine the fire vulnerability of historic buildings (Watts Jr., 1996).

It is not known exactly how much of the world's cultural heritage has been lost to fire. Fire loss data is collected only on factors related to the cause and origin of the fire. There is no fire loss data by historical significance or building age. The vulnerability of historic buildings to loss or damage from fire increases with each major fire that destroys a historic building and its contents. Historic buildings are not buildings that can be replaced, but rather irreplaceable artifacts whose value cannot be recovered through insurance payments (Watts Jr. & Kaplan, 2001).

The use of existing and abandoned historical buildings by changing their functions or preserving their existing functions is quite common today. In the face of this situation, some administrations have attempted to prepare regulations specific to these historical buildings. However, although some of the emerging approaches are more progressive than others, most of them contain incommensurable terms such as "minimum", "acceptable", "sufficient" and "reasonable". This uncertainty puts the designer, the property owner or user and the inspecting institution in a difficult position (Watts Jr. & Kaplan, 2001). As can be understood from all these uncertainties, it is very difficult to determine the behavior of historical buildings during fire through regulations.

Therefore, it is necessary to develop methods to assess the fire safety of built cultural heritage assets, taking into account their specific characteristics and focusing on the protection of heritage values. However, for most countries, conducting multi-hazard risk analysis for a large number of cultural heritage assets often requires unachievable efforts and budgets. Therefore, assessing risks for a large number of assets with limited resources is only possible when based on simple methodologies (Romão, Paupério, & Pereira, 2016). The development of risk assessment methods for historic buildings should also take into account the possibility of their application to a large number of historic buildings (e.g. in a region or across the country) without requiring excessive manpower and economic resources. Furthermore, given that historic buildings with different characteristics are likely to have different fire vulnerability factors, the specified methods should be able to account for these differences. Therefore, these methods need to be simple, yet reliable and versatile.

3.1. FRA methods for historical buildings

Fire assessment of historical structures can be applied at the scale of a single structure or at the scale of urban and/or rural settlements. Historical structures are generally located within old settlement areas and many old and new settlements are observed within these areas. In this sense, it is not possible to evaluate them independently from their surroundings in terms of risk assessment. In this sense, the complex structures of qualitative methods can be partly difficult to apply in large areas. Indicator-based methods (also called risk indexing methods) have been widely preferred in the literature in order to provide a simple and reliable way to determine the fire risk level of existing structures over large areas. Fire risk indexing systems are intuitive models of fire safety. They constitute the processes of analyzing and scoring hazards and other system features to produce a fast and simple estimate of relative fire risk. They are also known as rating tables, score schemes, ranking, numerical rating and scoring. Using professional judgment and past experience, fire risk indexing assigns values to selected variables representing both positive and negative fire safety features. The selected variables and assigned values are then processed through a combination of arithmetic functions to arrive at a single value, which is then compared to other similar assessments or a standard (Watts, 2016).

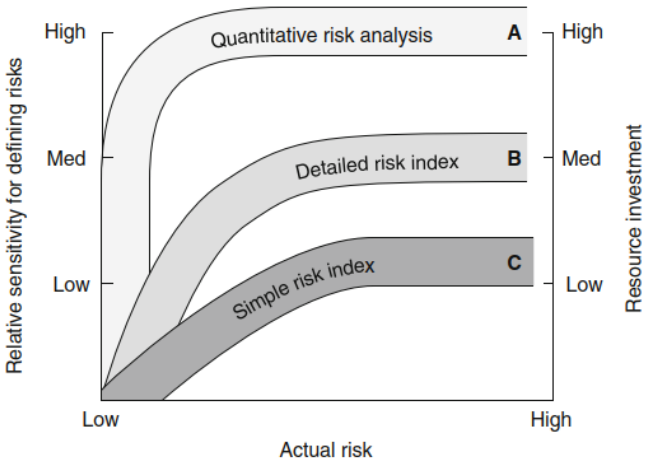


Fig. 5. Relative sensitivity for defining actual risk (Rosenblum & Lapp, 1989; Watts, 2016)).

Indexing methods are shown under the titles of "Semi-Quantitative methods" according to some sources and "Quantitative methods" according to some sources. This classification varies according to how FRAs are classified. However, the simplest explanation of this classification can be given through the graphic in Fig. 5 below. Even if the details of indexing methods are examined, they cannot provide results as sensitive as quantitative risk methods. For this reason, it is more possible to associate indexing methods with semi-quantitative methods (since they give a numerical value to the risk level, but this numerical value does not represent a definite risk value).

Within the scope of the study, the methods used in FRA research of historical structures in the literature are given below. As mentioned above, these methods are evaluated as "Semi-Quantitative" in some sources and "Quantitative" in some sources. The sources in question are presented under the titles of method name, year, place of origin, target structure (structure class) based on the study conducted by Salazar et al. (2021).

Table 1. FRA methods for historical buildings (Adapted from Salazar et al. (2021)).

Method / Year	**Origin**	**Target constructions**
GRETENER /1961-1968	Switzerland	Industrial buildings, but also used in other buildings
PURT – EURALARM /1972	Serbia	New and existing buildings
TRVB /1975-1987	Austria	New and existing buildings
ERIC /1977	France	Industrial and office buildings, dwellings
FSES /1978	USA	New and existing buildings
BOCA /1990-1996	USA	Existing buildings
ILHR/1995	USA	Historic buildings except nursing homes, hospitals and residential facilities
ARICA /1997-2000/2010	Portugal	Old urban centres
MESERI /1998	Spain	Low risk industrial buildings, but also used in other buildings
HFRI /1998-2001	UK	Historic house museums
FRIM-MAB /2000	Sweden	Multi-storey apartment buildings
SEPC /2002	Wales	Churches
FRACM /2002	Canada	Collections in museums considering the building characteristics

Table 1. continued

RAGER /2002	France	Movable objects in churches considering the building characteristics
FRAME / 2008	Belgium	New and existing buildings
MARIU /2011	Portugal	Existing buildings in old urban centres for fire risk mapping
FETAM /2013	Taiwan	Monuments and historic buildings
FRIM-HB /2014	Italy	Historic buildings
CHICHORRO /2016	Portugal	Existing buildings

When the risk definitions of the methods listed above are examined in detail, it is seen that some methods have similar formulations. This shows that the methods are developed over each other. In this sense, for example, although the FRIM-MAB and FRIM-HB methods are almost completely similar, the change in formulation is seen in the case of historical buildings. Due to such similarities, all these methods are grouped under three main headings according to Salazar et al. (2021):

a) Methods developed for ordinary structures and applied to cultural heritage assets or taking into account factors/criteria that are important for cultural heritage assets.
b) Methods developed for historical or older structures based on existing methodologies (Methods colored gray in Table 1).
c) Methods developed specifically for cultural heritage and historical structures.

The methods included in category “a” are; GRETENER, EUROALARM-PURT, TRVB, ERIC, FSES, BOCA, MESERI, FRIM-MAB and FRAME, respectively.

The methods included in category “b” are; ARICA, MARIU, CHICHORRO, ILHR and FRIM-HB, respectively. While ARICA, MARIU and CHICHORRO focus on old city centers, ILHR and FRIM-HB are created specifically for individual buildings. In addition, HFRI is partially accepted in this category because it focuses on historical museums.

The methods included in category “c” are; SEPC, FETAM, FRACM and RAGER, respectively. While SEPC and FETAM focus on historical structures, FRACM and RAGER are more focused on portable cultural assets.

4. Analysis of FRA methods for historical buildings

In light of the information provided above; the target structures for fire risk assessment in historical buildings are the “b” category, which is determined as the scope of the study. The study focused on the “b” category because the main target of the “a” category is not directly historical buildings, and the “c” category focuses on more symbolic structures and portable cultural assets compared to other historical buildings.

The methods in this category will first be analyzed based on the items specified in heading 4.1 below, and various inferences will be made from this analysis data..

4.1. Determination of analysis titles of FRA methods

When the methods in Table 1 are examined, different formulations and risk definitions are seen in each of them. This situation is due to the complexity of the general operation of the risk analysis, where different factors can coexist.

The ideal theoretical environment for conducting a risk analysis requires the probabilistic quantification of hazard, vulnerability and resilience. Both sufficient/reliable data and adequate analytical/numerical procedures are required to create probabilistic representations of these components. However, in many cases, especially in the risk analysis of cultural heritage assets, defining these components in a reliable probabilistic context becomes very complex (Romão, Paupério, & Pereira, 2016).

Probabilistic representation of risk is generally carried out on data obtained from past events. Probabilistic risk definition can be made for natural events such as earthquakes, floods, landslides or volcanic movements (Romão, Paupério, & Pereira, 2016). However, it is quite difficult and complicated to make a clear definition on fires, especially in historical buildings, due to the lack of data definition (Kincaid, 2022). When working on cultural heritage assets, the multidimensional nature of the asset's value and the complexity of its assessment are major conceptual hurdles.

To create a comprehensive risk assessment procedure and implement a framework within which the results can be regularly updated over time, the following key issues should be integrated:

a) Reliable and sufficient data for the development of appropriate hazard models.
b) Sufficient and reliable data regarding the assets at risk.

c) Appropriate procedures for modeling vulnerability.
d) Adequate models to predict the multidimensional consequences of the hazardous event.
e) Having sufficient human, time and economic resources(Romão, Paupério, & Pereira, 2016).

In the context of a risk assessment procedure for cultural heritage assets, the most difficult issue to address, regardless of the hazard in question, has been "d". Furthermore, in order to successfully address "a, b and c", issue "e" must be provided as a priority. All these fundamental issues will define the scope and comprehensiveness of the risk analysis and will be the basis for the successful regular updating and monitoring of the risk assessment results over time (Romão, Paupério, & Pereira, 2016). For this reason, it is important to have a simple methodology that can be used to determine risk reduction priorities or to identify assets that require more detailed data, especially in methods where many structures are included in the analysis and located in old settlements such as historical buildings.

In this context, the following analysis headings were determined to discuss the above outlined characteristics through the selected FRA methods (ARICA, MARIU, CHICHORRO, ILHR, HFRI and FRIM-HB):

Scale & Application Domain, Factors / Parameters, Number of Parameters, Output / Classification, Key Features, Input Type, Data Collection Time, Expertise Requirement, Report Format, Software Support, Validated Case Studies, Version / Mode, Sensitivity Analysis, Uncertainty Metrics, Update Cycle, Standards & Regulatory Compliance, Advantages and Disadvantages.

4.2. Analysis of FRA methods for historical buildings

For the comparative analysis of FRA methods, the headings determined above will be applied. First of all, the general definition of ARICA, MARIU, CHICHORRO, ILHR, HFRI and FRIM-HB methods and the sources used are given in Table 2 below. Table 3 includes a detailed comparison of the FRA methods with previously determined analysis headings.

Table 2. Calculation formulas for FRA methods

Method	Calculation Formula	Reference
ARICA	$FR_I = \frac{(1.20 \times SF_I + 1.10 \times SF_P + SF_E + SF_C)/4}{FR_R}$ *FR_I = fire risk assessment* *SF_I = ignition phase factor* *SF_P = propagation phase factor* *SF_E = evacuation phase factor* *SF_C = fire combat factor* *FR_R = reference risk factor*	- (Vicente, Silva, Varum, & Costa, 2010), - (Granda & Ferreira, 2019), - (da Mota, 2014), - (Almeida, 2013), - (Muculo, 2013), - (Santos, et al., 2011).
MARIU	$RL = E \sum_{i=1}^{11} WC_i \cdot SL_i$ *RL = risk level* *E = equalisation factor* *WC_i = weight of factor i* *SL_i = severity factor i*	- (Lopes, Coelho, & Rodrigues, 2011), - (Lopes, Coelho, & Rodrigues, 2012).
CHICHORRO	$RI = P \times G$ *RI = fire risk* *P = probability of fire ocurrence* *G = severity of fire consequences*	- (Gonçalves & Correia, 2016), - (Soares, 2021), - (Coutinho, 2017).
ILHR	$S = \sum_{i=1}^{17} w_i r_i$ *S = evaluation score* *w_i = weight of factor i* *r_i = normalized rating of factor i*	- (Rasbash, Ramachandran, Kandola, Watts, & Law, 2004), - (Kaplan & Watts, 1999).
HFRI	$(A \times B) = \sum_{i=1}^{11} A_i \times B_i$ *A × B = fire safety score* *A_i = value of factor i* *B_i = weight of factor i*	- (Kaplan & Watts, 1999), - (Watts Jr. & Kaplan, 2001).
FRIM-HB	$RI = 5.00 - S = 5.00 - \sum_{i}^{23} w_i x_i$ *RI = risk index* *S = safety score of the building* *x_i = score of factor i* *w_i = weight of factor i*	- (Arborea, Mossa, & Cucurachi, 2015).

Table 3. Comparative analysis of FRA methods for historical buildings

Feature	ARICA	MARIU	CHICHORRO	ILHR	HFRI	FRIM-HB
Scale & Application Domain	Historic urban fabric: streets, blocks, individual buildings	Urban building stock; mid-level technical expertise	Building-level, general purpose	Commercial historic buildings ≤1,115 m²	Historic house museums	Historic buildings; integrated with Carta del Rischio
Factors / Parameters	4 global (FGII, FGDPI, FGEE, FGCI); ~15 partial	11 SL × CP; E coefficient	4 global: POI (12), CTI (3), DPI (5), ESCI (7)	17 parameters (A × B)	11 parameters; w_i (%), r_i (0–5 Likert)	17 P + 6 N hierarchical
Number of Parameters	≈15	11	27	17	11	23
Output / Classification	Risk >1 → action needed; risk map; rapid screening	GR ∈ [38–1200]; 5 risk levels	Grades A++…F ("Very Low"–"Immediate")	Score; additional measures per code	Grades A++…F ("Very Low"–"Immediate Intervention")	RI [0–5]; lower RI = higher safety
Key Features	GIS integration; simplified & detailed versions	Rapid matrix; geographic mapping	Holistic optimization; simplified input mode	Heritage fabric conservation; flexible scoring	Performance-based; collection preservation focus	Policy & strategy oriented; heritage preservation
Input Type	Quantitative	Quantitative	Quantitative	Quantitative/Qualitative	Quantitative	Quantitative
Data Collection Time	Medium (1–2 days)	Low–Medium (1 day)	High (2+ days)	Medium (1–2 days)	Medium (1 day)	Medium (1–2 days)
Expertise Requirement	High	Medium	High	Medium	Medium	Medium–High
Report Format	Risk maps & tables	Matrix tables	Summary tables & score charts	Compliance reports	Score tables	Risk report format
Software Support	ArcGIS, QGIS integration	Microsoft Excel; ArcGIS; QGIS	Custom scripts (Python, R)	None	Microsoft Excel	Carta del Rischio GIS; ArcGIS
Validated Case Studies	Paranhos, Seixal, Viseu	City-wide applications	Amarante pilot	Wisconsin historic buildings	House museum pilot	Rome public office
Version / Mode	Simplified version available	None	Simplified mode available	None	None	None
Sensitivity Analysis	Available	No	Available (parameter ranges)	No	No	No
Uncertainty Metrics	None	None	Yes	None	None	None
Update Cycle	Periodic reviews	Periodic updates	Project-based	Code revision-based	Regular form updates	Continuous updates
Standards & Regulatory Compliance	Compliant with local codes	Aligned with general risk standards	Independent methodology	Direct code compliance	Museum standards	Italian risk mapping standards
Advantages	Detailed analysis; geographic integration	Fast; user-friendly	Holistic & optimizable	Heritage focus	Collection preservation	Integration; policy focus
Disadvantages	High expertise; time-consuming	Limited risk detail	Complex; tool dependencies	Limited to small buildings	Narrow scope	Complex hierarchy

5. Discussion

The differences between the scope, purpose and application features of ARICA, MARIU, CHICHORRO, ILHR, HFRI and FRIM-HB methods reveal the strengths and weaknesses of each method in terms of target scale, data requirement, interpretation style and legislative compliance.

When we look at the scale and purpose compatibility, ARICA and MARIU are approaches designed to perform risk mapping at the urban fabric level, providing rapid scanning opportunities at the block and street scale. While ARICA provides detailed spatial analysis with a data collection period of 1–2 days thanks to the integration with geographic information systems; MARIU offers a practical solution using a simple Excel-based matrix completed in just one day. In contrast, CHICHORRO and FRIM-HB simultaneously evaluate both the probability of fire occurrence and the severity of its consequences with building-based holistic optimization principles; however, comprehensive parameter sets and special automation scripts increase the application time and the level of expertise required.

In terms of speed and user-friendliness, MARIU has the highest ease of use and speed advantage among all methods, while ARICA balances the advantages of moderate complexity and rapid geographic analysis. While CHICHORRO and FRIM-HB require detailed modeling, ILHR and HFRI offer direct regulation or form-based scoring, providing relatively less automation in the field, but a more limited scale and scope of objectives

In terms of Expertise Requirement and Automation, ARICA, MARIU and FRIM-HB offer integration with common geographic or spreadsheet software (ArcGIS, QGIS, Excel) to support data processing and mapping automation; whereas CHICHORRO's Python/R scripts provide in-depth analysis but require initial development. ILHR and HFRI operate via manual form updates and score tables, thus offering limited automation possibilities but offering the advantage of direct compliance with legislation or museum standards.

In terms of uncertainty and sensitivity analysis, ARICA and CHICHORRO allow sensitivity control with parameter ranges against the variability of conditions. Since most of the other methods do not include uncertainty metrics or formal sensitivity analyses, additional Monte Carlo or probabilistic calculations can be suggested to increase the reliability of these models.

Regarding standard and regulatory compliance, ILHR and HFRI fully serve the relevant code and museum standards, while ARICA and MARIU provide a more flexible compliance, while FRIM-HB is directly integrated into the Italian "Carta del Rischio" framework.

Consequently, considering the scale, time constraints, data access possibilities and regulatory requirements required by the institution or project:

- MARIU for rapid, city-wide screening,
- ARICA for geographically detailed analysis,
- CHICHORRO or FRIM-HB for comprehensive optimization at the building scale,
- ILHR or HFRI should be preferred for situations requiring official approval and regulatory compliance.

6. Conclusions

In this study, six different fire risk assessment methods ARICA, MARIU, CHICHORRO, ILHR, HFRI and FRIM-HB were compared in terms of scale, data requirement, automation level and regulatory compliance. Among the examined methods, there is a clear distinction between rapid urban scale scanning (MARIU), block and street level analysis supported by geographic information systems (ARICA), building-based holistic optimization (CHICHORRO, FRIM-HB) and regulation-based scoring (ILHR, HFRI). This differentiation reveals that each method requires a multi-dimensional set of selection criteria, from the number of parameters to uncertainty and sensitivity analysis, from software integration to field implementation time. Therefore, not only speed or detail but also automation capability, level of expertise and regulatory compliance should be equally taken into consideration in risk assessment processes.

A holistic and sustainable fire risk management in historical building groups can only be achieved by consistently matching the technical capacity of the selected method with the application context. In this context; the size and depth of coverage of the parameter set, the level of automation and the presence of uncertainty analysis tools; whether the risk model will be applied at the city scale or on a single structure basis; data access, data quality and timeliness; and the harmonious construction of stakeholder participation dynamics (interaction mechanisms between fire departments, conservation experts, local governments and property owners) are of critical importance. In the selection of the method, not only the quantity and quality of the available data, but also how the model outputs will be interpreted by decision makers and the ways of integration into response planning should be taken into account. Furthermore, the systematic inclusion of continuous monitoring and update cycles in the methodology; for example, automatically updating the findings obtained through periodic field inspections via digital platforms, will both maintain the real-time validity of risk scores and allow for flexible revision of long-term response strategies. This approach will also support different scenario analyses, ensuring that resource allocation, emergency training and policy development are carried out within an integrated framework, thus paving the way for the dynamic improvement of fire safety standards specific to the historical texture.

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