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FLAME: A Parametric Fire Risk Assessment Method Supporting Performance Based Approaches

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Abstract. A fire risk assessment has always been a challenging task. Performance-based approaches to fire engineering have shown that risk-based decisions and fire scenarios are fundamental elements that must be considered in fire safety strategies. A correct assessment of the fire risk allows all the involved stakeholders to identify a specific strategy from among a variety of possibilities. A risk assessment is the best tool to identify comparable fire protection strategies and to measure the reduction in fire risk that can be obtained with each specific prevention and protection measure, i.e., by means of different fire safety strategies. The present paper illustrates a method that takes into account several well-known methods, even some that were developed as far back as in the early seventies. The method is named "FLAME" (Fire Risk Assessment Method for Enterprises). FLAME considers fundamental fire safety aspects instead of making use of sophisticated and time-consuming methods like CFD. FLAME uses the "Fire Safety Concept Tree", which is explained in detail in the NFPA 550 Standard, as a reference scheme. The method allows the risk to the occupants to be evaluated separately from the risk to the building. Over the years, we have tested the method considering different kinds of buildings and occupancies. We here report the results of an application of the FLAME method to hospitals and health-care facilities. Overall, about 300 compartments (overall size of about 60,000 m^2) were analysed, including two hospitals of about 200,000 m^2 each. The results of the risk estimation with the FLAME code have been found to be coherent with Italian fire code prescriptions. About 44% of the compartments were defined as being at a Medium risk and 39% as being at a high risk (according to the Italian Fire Code). More than 60% of the hospital compartments were defined as being at a High risk. A good agreement was obtained between the RSET results with those of the method proposed in FLAME when using the current performance-based regulation criteria. The RSET estimation in FLAME considers the occupants' behaviour and the actual characteristics of the occupants in clinics or hospitals, who often have difficulties due to reduced mobility or an incapacity to understand emergency instructions.

Keywords: Fire risk assessment, Structural fire safety, Fire safety management system

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Abbreviations

IPC	Ignition probability class
FGC	Fire growth category
EL	Exposure level
PMT	Pre-movement time
RSET	Required safe egress time
ASET	Available safe egress time
ORL	Occupants' risk level
FLC	Fire length category
FS	Fire severity level
FFE	Fire fighting expediency
FFM	Fire fighting means
CC	Compartment configuration
PRL	Property risk level
PCL	Protection category level
ALL	Alert system

1. Introduction

The first shift from the complying/not complying strategy of fire protection towards a risk-based approach dates back to the '70s. At that time, the Fire Safety Concept Tree (NFPA 550, [1]) and the so-called Appendix D from GSA (General Services Administration, 1972) [2] became the main documents used to describe this risk-based approach to fire safety.

Before the publication of NFPA 550 ([1], latest edition, NFPA, 2007), the components of a fire protection system were treated as being independent of one another. In this document, it is possible to read that this lack of an inter-dependent approach: "can lead to unnecessary duplication of protection. On the other hand, gaps in protection or a lack of desired redundancy can exist when these features are not coordinated".

The relevant features of these earlier methodologies included the concept of relative risk and acceptability of the risk level, the inclusion of management procedures as a means of achieving acceptability, the use of probability to describe the mean performance of fire safety and the adoption of an event tree structure, which was used to define connections between the components of a system and to compare their performance (Fig. 1).

The logic behind the tree is easy to understand: the "OR" and the "AND" operators determine whether a single element in the upper layer is dependent on at least one element in the lower layers, or on the concurrence of all of them.

The highest level of the tree is the "Objectives of the fire safety strategy" element, which is also the final stage of the approach: if the objectives are met, then safety is achieved.

The adoption of this procedure implied abandoning a simplistic and potentially non-conservative approach which, in many cases, linked the total fire load to the fire risk level, but ignored or neglected other factors. However, in order to assess the fire risk in a specific compartment, more information than just the total fire load is required: the fire dynamics (e.g., HRR), a correct layout of the compartment, the prevention measures and the elements that composed the fire strategy already in place.

Other methodologies have since been proposed with different purposes: to deal with specific cases, that is, with industrial or civil buildings, and/or to adopt a method enforced by the local laws and regulations, etc. ISO 31010 provides a list of risk evaluation techniques and their capability of identifying or of evaluating a risk. Thirty-one techniques are described in the standard, including check-lists, what-if, fault and event tree analysis, and consequence-probability matrices. The FLAME method, according to the classification given in the standard, falls into the category of "risk index methods". A risk-index, according to the definition of the standard, is a semi-quantitative measure of risk, which is derived using a scoring approach with ordinal scales. Indices allow a risk ranking to be drawn up against a common criterion, and they permit a range of factors that have an impact on the level of risk to be condensed into a single numerical score of the level of risk. Inputs are derived from the analysis of the context (description of the system), considering various parameters in order to overcome the limitations of qualitative judgements.

The Fire Risk Assessment process could be defined, according to ISO 16732-1:2012, as a part of a more extensive process in which the fire risk goals and objectives are first defined, and the acceptability of the risk concludes the process. If the fire risk assessment procedure produces an unacceptable outcome, then the initial design specification must be revised, and the procedure should be repeated (see Fig. 2).

According to the Fire Risk Assessment approach (ISO 16732-1), fire risk methods may be classified as qualitative or quantitative, or even as a combination of the two.

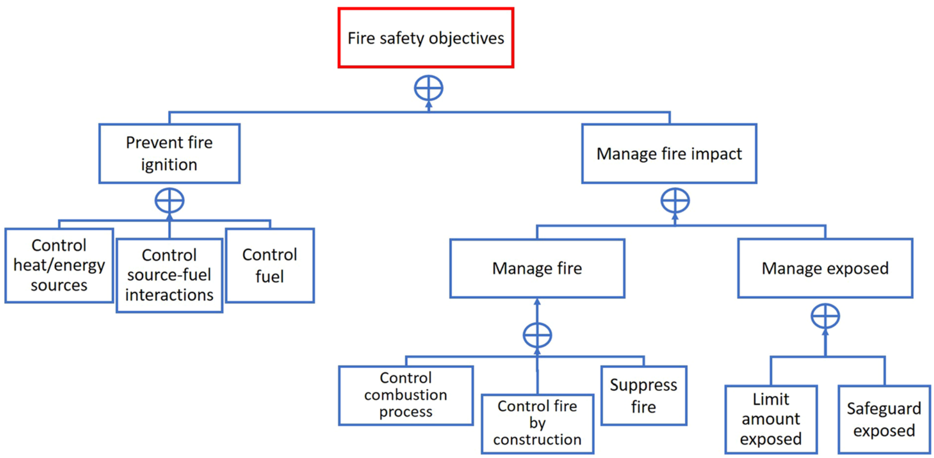

Figure 1. Fire safety objective tree, from NFPA 550 [1].

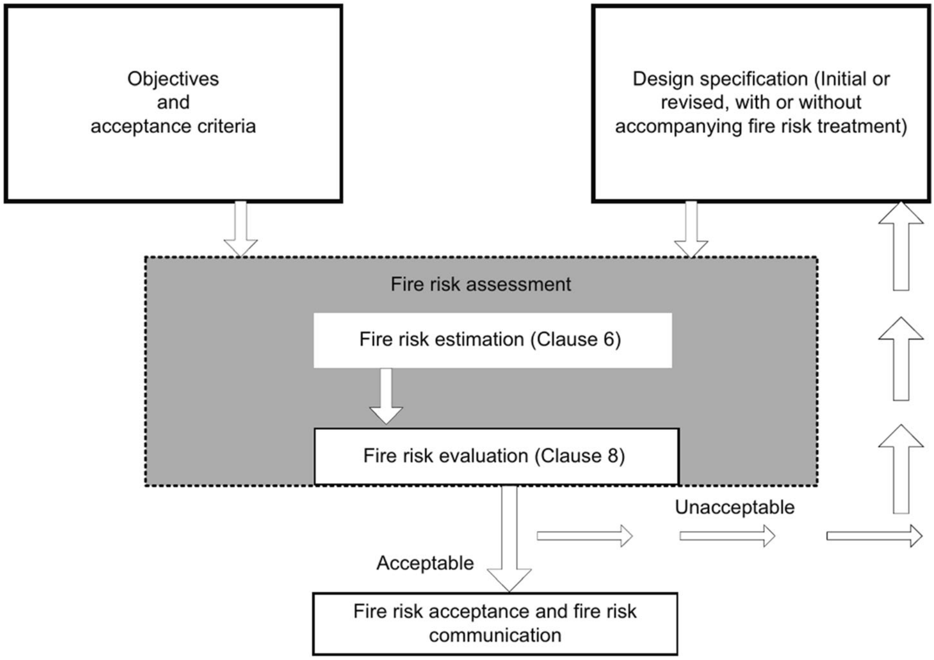

Figure 2. Fire risk management flowchart, taken from ISO 16732-1:2012 [3].

As computational power has increased, a noticeable improvement in the consequence assessment field has occurred. However, the increases in the possibility of modelling fire dynamics, even in a complex environment (industry, tunnels, high-rise buildings, heritage buildings, etc.) have not been accompanied by similar advances in the probability of occurrence assessment methods or in the data and methodologies used to estimate the fire dynamics associated with specific fire events. These advances have only been seen in specific fields. A number of quantitative methods have been used for several decades in the industrial risk field (associated with nuclear, oil & gas, chemical and process industries), including fault and event trees, Monte Carlo simulations, Markov chains, decision trees, FN curves, probability analysis methods as well as CFD and FEM methods for the analysis of the consequences.

Over the years, this increasing computational power has led to the diffusion of performance-based approaches based on advanced simulations, but which can also be conducted on ordinary personal computers or on the Cloud. Unfortunately, as a consequence of these advantages, many people have begun to confuse simulation with a performance-based approach to fire engineering and have started to rely on simulation, even for simple problems that could be solved using simple correlations. In fact, some fire engineers who carry out simulations do not know about the fundamentals of fire dynamics or the fire risk assessment concept, which should be the initial step of an efficient, performance-based approach where fire scenarios should be considered with regards to the probability of occurrence and of the consequences.

A more comprehensive risk assessment may be considered as the basis of a proper fire safety strategy. The Fire Risk Assessment is a process that can be used to estimate and evaluate the fire risk pertaining to buildings, facilities and/or processes. The Fire Risk Assessment process includes the evaluation of relevant fire scenarios, with their associated frequencies and consequences, using one or more acceptance criteria. According to this process, it is equally important to define both the occurrence and the consequences associated with potential scenarios. An unbalanced approach (i.e. a probabilistic assessment of occurrence, without estimating the consequences or making an in-depth assessment of the consequences, regardless of the probabilities associated with that particular event) could lead to a partial fire risk assessment with a consequent incorrectly sized fire strategy. A precise workflow should be drawn up to obtain a fire strategy that is coherent with the identified fire risk. The fire risk should be estimated during the assessment and then evaluated against an acceptance criterion. The initial estimation should consider, as already mentioned, both the probability of occurrence and the consequences. These should be calculated explicitly in a quantitative way. The estimation phase should start when the objectives and acceptance criteria have been established, together with specifications pertaining to the structure, or areas of the structure, and to the process that has to be assessed. The specifications of the context should be based on quantitative assumptions and a selection of the properties that have an effect on the calculation of the fire risk (number of occupants, number of exits, fuel load density, etc.). The fire risk assessment should include a systematic identification of the fire hazards and fire scenarios.

FLAME is a method that uses an index-based approach. The method was conceived to deal, in a simplified way, with the complexity associated with a quantitative approach to the estimation of both probability and frequency. Parameters are derived from a variety of values that are used to create indices which describe a specific context. The proposed model has the aim of guaranteeing an understanding of the relationship between changes in the design and changes in the resulting fire risk, where any changes may be associated with technical and/or management issues. An index-based approach, even though not comparable with a full quantitative fire risk assessment, in terms of assessment detail, could be used as a first approach to fire risk estimation, even in the first stages of the design process. The use of indices, based on a set of values, makes it possible to avoid a full qualitative approach (such methods as HAZID, Bow-Tie, Risk Matrix, etc.), which may not be able to offer a preliminary estimation and/or an initial assessment of the risk reduction associated with different measures selected as part of the overall fire safety strategy, or the risk reduction of a preferred strategy versus alternative ones.

1.1. Fire Risk Indexing: State of the Art

In the SFPE Handbook [4], Watts reported that "fire risk indexing is the process of modelling and scoring hazard and exposure attributes to produce a rapid and simple estimate of the relative risk. The concept has gained widespread acceptance as a cost-effective prioritization and screening tool for fire risk assessment programs. It is a useful and powerful approach that can provide valuable information on the risks associated with fire''.

The same document underlined the several aspects and cases in which a fire risk indexing approach could be applied: in cases where a great level of sophistication is not required, or risk screening will be cost-effective and where there is a need of risk communication. Its effectiveness in underlining global fire risk assessment issues has made this approach feasible for the members of staff who are encharged with the responsibility of fire risk management, but also for people who are not used to fire safety concepts, due to its level of simplification. The significance of fire risk indexing has been known since the first studies in the field.

Fire risk indexing features can generally be summarised in a quick and semi-quantitative approach (money and time saving), with a broad range of applicability, for the integration and quantification of several factors (both countable and qualitative), in a transparent decisional procedure.

A brief description of the methodologies which have inspired the development of the FLAME methodology is reported hereafter, together with the logic behind them and the key elements that were identified.

1.1.1. The Gretener Method First described in scientific literature by Gretener [5], this method can be used to calculate the fire risk of industrial buildings and other objects. The method was further improved by Kaiser [6] and Fontana [7] and recently used by Brzezińska et al. [8] as a basis for an assessment of fire strategies in power stations. It was among the first to consider the possibility of describing the fire risk level by resorting to arithmetic evaluations. The risk is calculated as:

$$R = A \times B$$

where A is the probability of fire ignition and B represents the expected hazards. It is expressed as the ratio between the potential hazards and the protection measures as follows:

$$B = \frac{P}{N \times S \times F}$$

where P, N, and S are indices that define the potential hazards, standard fire safety measures and special fire safety measures, respectively. F stands for the fire resistance of the building.

1.1.2. The Fire Risk Assessment Method (for) Engineering (FRAME) The FRAME method, whose first version was developed in 1988 by Erik De Smet (updated by De Smet, [9]), is derived from the Gretener application and expands it with a detailed compilation of the parameters used to calculate hazards and of the effect of protection measures.

The key features of FRAME are:

(a) An adequate fire safety strategy can be obtained from a balance between the fire threat, fire protection and exposure to fire;
(b) A major fire occurs when all the protection systems fail;
(c) A fire strategy is drawn up for each compartment and evaluated according to the exposure of the occupants, the buildings and the activities.

The main indices are P (Potential hazards), A (Acceptable risk level), D (Fire protection) and R, the resultant level of risk (which is different for occupants, buildings and activities).

The method is structured by means of a flow chart, which is based on a cause-effect logic: each node represents a cause/effect link that could influence the exposure level, fire severity and/or the occurrence probability and acquired protection level.

FRAME estimates the initial level of risk, R_0, which is defined as:

$$R_0 = \frac{P}{S} \cdot F_0$$

where F_0 is a measure of the fire resistance of the building, without considering the effect of the protection measures. The risk is declined as R, R1, R2 for buildings, occupants and activities, respectively, where each outcome is derived from a different combination of the P, A and D indices. For example, the fire risk for people is calculated as:

$$R_1 = \frac{P_1}{A_1} \cdot D_1$$

where P1 depends on the parameters that account for the possibility of a fire spreading, the ignition probability, compartment surface, venting, access and level, while A1 depends on the estimated evacuation time, ignition sources and environment characteristics, and D1 considers the fire protection plus the escape factor (referring to the automatic detection of fire, possible evacuation paths, smoke venting etc.).

The final step is a comparison between the risk level and the acceptability factor; FRAME suggests the protection measures that should be implemented according to the risk severity.

FRA-Mini, which is a simplified and qualitative version of the original FRAME method, was developed by De Smet. As in FRAME, the evaluation of the fire risk is conducted for both the property and occupants.

Evaluation weighted checklists, derived from the FRAME sub-factor calculations, are used to minimise the complexity of the method. Such checklists allow a balanced evaluation of several parameters to be used to produce sub-classes that are subsequently utilised in the decision tree process: the thus derived fire risk classes are compared with the protection categories. These were inspired by the qualitative risk evaluation method described in the EN10501 and EN954-1 standards for the safety of machinery.

As a simplified analysis method, FRA-Mini is somewhat limited, as it should only be used to make a qualitative fire risk assessment. Classifying risks and protections into 5 classes and five categories, it should be considered a mere decision tool. In practice, there is a wide variety of possible types of damage and a broad spectrum of available protection systems. When, as in many cases, a qualitative risk assessment is adequate to make a decision on the required protection level, the diversity of factors of influence is so large that a more gradual approach of risks and protections is needed to develop a tailor-made (fire) safety concept. In such cases, the FRA-Mini decision tree results in a "Not in scope" or "non-applicable" indication.

When a quantitative fire risk assessment is necessary, e.g. for the definition of an alternative or equivalent fire safety concept, FRAME, or a more elaborate method, should be used, in agreement with the stakeholders.

1.1.3. The Building Fire Safety Evaluation Method (BFSEM) This method was developed by Fitzgerald [10] and can be considered as being part of the hazard-consequence assessment group. BFSEM has a flow-chart structure, where the efficacy of the protection systems is tested at each step. Through the BFSEM, it is possible to evaluate the likelihood of ignition, fire growth, and the spread of a fire through an existing building or a new building for which fire protection plans have to be developed, focusing on such factors as the fuel load, the occupancy characteristics, active fire protection features and structural features.

1.1.4. The Fire Safety Evaluation System The Fire Safety Evaluation System (FSES) was set up to verify compliances with the NFPA 101 standard (NFPA 101, Life Safety Code, [11]), for certain institutional occupancies. FSES was developed to provide a method which could be used to determine fire safety measures that would provide an equivalent level of fire safety to that provided by the Life Safety Code. It was conceived in particular for health care facilities.

The objective of FSES is to obtain an easy-to-apply evaluation tool and to define an equivalency concept of the fire safety level, which can be used to create alternative designs that provide an equivalent level of safety and which would satisfy the regulations in force. FSES relies on different concepts of fire safety:

- The fire zone is defined as a space that is separated from other parts of the building by floors, fire barriers and/or smoke barriers;
- The characteristic behaviour of healthcare facility guests is considered to define the risk. This includes such aspects as:
    - Mobility
    - Density
    - Fire zone location
    - Staff-to-patient ratio
    - The average age of the patients
- Thirteen fire safety parameters are defined;

- A fire safety strategy is considered to be redundant: a single failure of the system will not result in significant losses (the adopted fire strategies are containment, extinguishment and movement of people);
- Equivalency: FSES compares the fire safety level attributed to each fire zone with the fire safety level defined in the NFPA 101 standard, that is, it compares the calculated levels with the minimum values defined in the standard.

1.1.5. The Dow Fire and Explosion Index The Dow Fire and Explosion Index (F&EI, [12]) was developed by the Dow Company back in 1964 to face issues related to the identification of areas in chemical plants at risk to significant economic losses. F&EI is a tool that can be used to quickly examine and identify which sections of plants constitute a significant fire and/or explosion hazard, depending on the involved processes and substances. According to this method, the plant is divided into different units which are treated individually. The F&EI approach is semi-quantitative: indices are often designed according to experience and information obtained from accident records.

The material factor and process unit hazard factor contribute to defining the outcome (F&E Index), as shown in Fig. 3.

2. The FLAME Method

FLAME is a new method that can be used for the estimation of the fire risk in workplaces. The method is based on a semi-quantitative parametric code that enables a "speditive" evaluation of the acceptability of certain fire safety measures adopted on the basis of the severity of the fire scenario.

FLAME was inspired by some QRA models, such as that of Gretener [5], FRAME [9] and FRA-Mini [13], and its procedure is coherent with the most recent Italian legislature on fire safety. The method is based on the Fire Safety Concept Tree and has the typical structure of fire risk indexing methods.

Compared to other methods, FLAME has a specific feature: the differentiation between two different groups of indices, associated with different targets (i.e., humans and assets). In this way, FLAME allows specific fire risk values to be defined for people and structures, with different acceptability criteria and, consequently, the necessity of adopting different measures to reach an adequate fire safety level. The fire risk level in FLAME is obtained from the combination of the factors that increase fire severity and the elements that contribute to mitigating fire hazards. Severity, which is among the first group, is defined as a function of the fire load, fire typology, and the vulnerability and exposure to fire of the involved people, while the mitigating elements are functions of the structural characteristics of the building, mobile or fixed protection equipment, the escape system and organisational procedures in the case of an emergency.

An essential aspect of this approach is the combination of both hard and soft factors, i.e., related to both structural and management parameters, to describe the risk level.

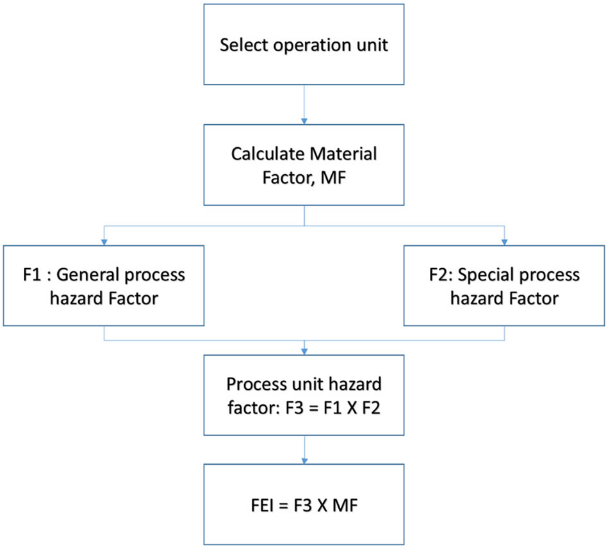

Figure 3. The Dow Fire and Explosion Index (F&EI) workflow. Adapted from [12].

Apart from the key elements that describe a fire hazard, scores are assigned to fire protection (active and passive) measures so that fire safety management aspects can be evaluated against specific indices to reduce or confirm negative performances.

Fire protection is scored considering the definition of the Protection Categories. This approach, here applied for the first time to fire safety assessment (in line with FRA-Mini, [13]), is derived from the EN-ISO 12100:2010 [14] and ISO-EN 13849-1 [15] standards.

The method uses weighed checklists, matrices, simplified algorithm applications and implementation of the basic concept of fire safety engineering throughout the process. Each step of the FLAME evaluation procedure is based on referenced literature in the fire safety field. The basic elements of fire safety are included in FLAME as they are concepts that were derived from the milestones of fire safety science at a global level: the SPFE Handbook [4], for the design of fire scenarios, as well as movement and evacuation timing during an emergency (i.e. Sec. 3 Chaps. 5, 6, 13 and 14), and Karlsson and Quintiere [16] and Quintiere's [17] publications, which were used to build the logical structure of the software.

Ignition frequency is defined according to a statistical study conducted in Finland by Tallander and Rahikainen [18] and Tallander [19], and in Sweden by Sandberg [20].

The Required Safety Egress Time for occupants (RSET) is adopted in FLAME as a key-node of the evaluation process; this concept was not included among the relevant elements in standards in Italy before the publication of the new Italian Fire Code [21]. RSET is estimated in particular according to the work of Marchant [22] and Sime [23], but the basic concept can be traced back to several building code documents and standards that incorporated this approach. Among them, the C/VM2 Verification method [24], the Building Code of Australia [25], and the ISO TR 16738:2010 [26] and PD 7974:2004 [27] standards are worthy of mentioning.

The FLAME structure is a logical, systematic flow where the main fire elements and issues can be defined through several parameters, classified (according to the intensity level of the parameter) and combined: two different logical flows are employed for the definition of the risk to occupants and to property, as the safety of the occupants is more time sensitive than property protection, since the first is mainly related to the Available Safe Egress Time (ASET). The dual evaluation of the method guarantees the possibility of obtaining a more specific and effective evaluation of the required safety level for the safeguarding of people and for the tenability of structures. For example, the fire load parameter is not a key parameter that needs to be considered to estimate the risk for the occupants, while it is of key importance for the estimation of the risk to property.

The method does not take into account the domino effect of fire from one compartment to another, which is inopportune as far as the safety of the occupants is concerned: once within the chosen compartment, the ignition probability and the typical fire growth of the occupancy are defined and the severity of the fire is evaluated with respect to the occupants' capability to escape, which in turn depends on their characteristics and on the alert system. The evaluation is focused on the early phase of the fire, when tenable conditions of the compartment are still in place. For this reason, the fire load index is not used to assess the occupants' risk level, while it is considered for the property risk level.

The fire load, and hence the duration of the post-flashover, that is, the fully developed phase of the fire, is instead a key factor in determining the risk to the structure. It is expected that the occupants will have safely evacuated the compartment where the fire originated prior to the flashover.

A fire risk estimation should be conducted considering different aspects, on the basis of whether the vulnerability is connected to the occupants or to the assets and structures (including business continuity), since different vulnerabilities have different tenability and acceptability criteria (e.g. the total available fire load is more important for business continuity and property protection than the ASET time, while the latter is a fundamental parameter for estimating the exposure of occupants to the risk of fire).

The probability of a fire igniting is considered a key-factor to assess the occupants' risk, while it is not a critical factor for the property risk evaluation. This difference concerning the property evaluation is easy to understand: if the safety of the people who are present is the main concern, the sooner the evacuation takes place, the safer the compartment. Moreover, a fast fire, involving a low fire load, is considered more dangerous than a slow fire involving a significant fire load. Consequently, the occupants' algorithm is time-based, and the fire load parameter does not play a role (while the worst case for property considers a higher fire load). On the contrary, it is relevant to assess whether efficient ignition sources are present in the compartment and to what extent they influence the fire spreading, once it has ignited. The probability of ignition is defined using classes of values, whose intervals are defined by considering the use of frequencies, as derived from technical literature. Classes do not differentiate between ignition sources.

The workflow adopted in FLAME is described systematically hereafter.

2.1. The Occupants' Fire Risk Chart

The occupants' fire risk evaluation flowchart is presented in Fig. 4.

The occupants' fire risk depends on the exposure level (EL) index and the Pre-Movement Time (PMT) Index. EL accounts for the probability of a fire igniting and quickly spreading in such a way that the occupants are threatened by heat stress or smoke. The PMT index accounts for the capability of the occupants to escape from a dangerous area. These two indices depend on several factors, as detailed below.

The outcome of the chart is the assessment of a risk level, based on a classification from 1 to 6. FLAME also reports the Italian ranking (according to Ministerial decree 10/03/98, [28]), which identifies "Low", "Medium" or "High" levels of fire risk, with a very simple discretization.

2.1.1. The Ignition Probability Class The ignition probability class (IPC) is derived from literature data on ignition frequency. In the present work, the ignition rates proposed by Tillander [18, 19] and Rahikainen [29] are used as the basic input (Table 1). No specific Italian data are available, and the selected sources appear to be conservative, as they are related to wooden constructions, which are not so common in Italy. The classification (Table 2) is made according to the ignition probability class, which is obtained as follows:

$$IPC = P_{ign}A$$

where P_{ign} is the frequency of ignition (the number of fires per year—square meter, shown in Table 2), which univocally depends on the activity carried inside the building. The values are multiplied by the floor area (A) and rated to obtain the basic ignition probability class (IPC, ranging from 0 to 4).

Occasional or secondary ignition sources may alter the ignition occurrence frequency, as a result of heating and electrical installation defects, the secondary use of hot points and/or flammable materials and human behaviour. FLAME considers the effect of different kinds of ignition sources: the ignition class should be increased (e.g. from IC 0 to IC 1) for each of the aggravating factors listed in Table 3. Enhancing factors act by adding points to the primary IPC score. For example, the presence of smokers in the compartment will raise the IPC by 2 points. Scores are defined in FRA-Mini [13] and included in FLAME.

2.1.2. The Fire Growth Category The fire growth category (FGC) is estimated according to the SFPE Handbook fire curves (Fig. 5). The curves are defined as α-t squared and represent the Heat Release Rate (HRR) of the fire versus time,

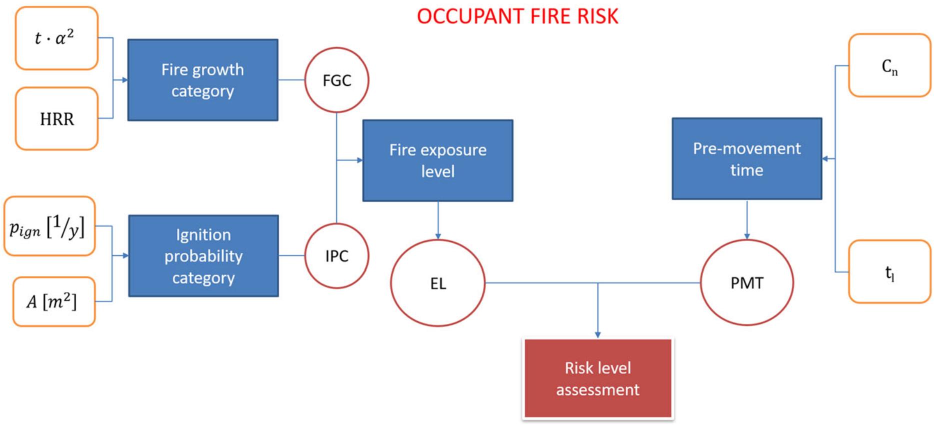

Figure 4. The occupants' risk evaluation tree adopted in FLAME. The red circles indicate indices defined by numerical values in yellow boxes. C_n stands for the occupants' characteristic values, t_l for the base time and p_{ign} for the probability of ignition.

where t_α is the time at which the heat output of the fire reaches 1 MW. The fire growth category (hence α) is defined by considering the type of material stored in the compartment, as in Table 4.

2.1.3. The Required Safe Evacuation Time for occupants Several variables in Fire Safety Engineering can influence and allow the total evacuation time to be estimated, depending on the occupants' characteristics (also from a social-psychological point of view) and on the structural complexity of the building; all of these

Table 1
Frequency of Ignition (P_{ign}) on the Basis of the Occupancy; The Proposed Values are the Means of Three References, That is, Tillander [18, 19] and Rahikainen [29]

Occupancy	P_{ign} [10^{-6} occurrence/y · m^2]
Offices	2.27
Educational buildings	2.52
Warehouses	2.76
Transports-rescue and service buildings	2.8
Assembly and gathering	3.98
Residential	4.96
Commercial	5.34
Healthcare	6.74
Industrial	8.0
Combustible industries	130.0

Table 2
Ignition Probability Class, Defined on the Basis of P_{ign} and the Compartment Surface (A)

Specific ignition frequency (y^{-1})	Ignition probability class, IPC
$<1 \cdot 10^{-3}$	0
$1 \cdot 10^{-3} < f < 1 \cdot 10^{-2}$	1
$1 \cdot 10^{-2} < f < 2 \cdot 10^{-2}$	2
$2 \cdot 10^{-2} < f < 1 \cdot 10^{-1}$	3
$> 1 \cdot 10^{-1}$	4

Table 3
Enhancing Factors for IPC, from FRA-Mini [13]

Enhancing factor	Points added to IPC
Open flame heat generator inside the compartment	1
Gas heating, without leak detector or extinguishing system	1
Open flame furnace fed by wood or waste materials	2
Electrical equipment not in compliance with local regulation	2
ATEX Zone 1	6
ATEX zone 1, NEC: Class I Div.1	4
ATEX Zone 2 NEC: Class I DIV.2 area	2
ATEX dust explosion zone 20/21/22	4
Combustible dust generation without abatement system	2
Painting, spraying or coating with flammable products; use of flammable solvents or glues; without any separation with main ambiance	4
As above, inside a dedicated area, with air extraction system	2
Uncontrolled human behaviour (smokers)	2

characteristics may be computed using either software [30, 31] or analytical methods [4].

The Available Safety Egress Time (ASET) is estimated as the time interval between the onset of fire and the moment when the conditions in the compartment become untenable, e.g., due to smoke and/or specific heat thresholds. The Required Safety Egress Time (RSET) is defined as the amount of time (measured from when the fire ignites) that is required for the occupants to evacuate a building or space and reach the exterior of the building or a protected exit enclosure.

When ASET is higher than RSET, people can evacuate safely. Conversely, when ASET is lower than RSET, evacuation takes place in hazardous conditions, and injuries to people cannot be excluded.

RSET can be considered as the sum of several time intervals, each one of which has a specific meaning, as indicated in Fig. 6. The definition of RSET, regarding its different components, can be found in several international fire standards: the

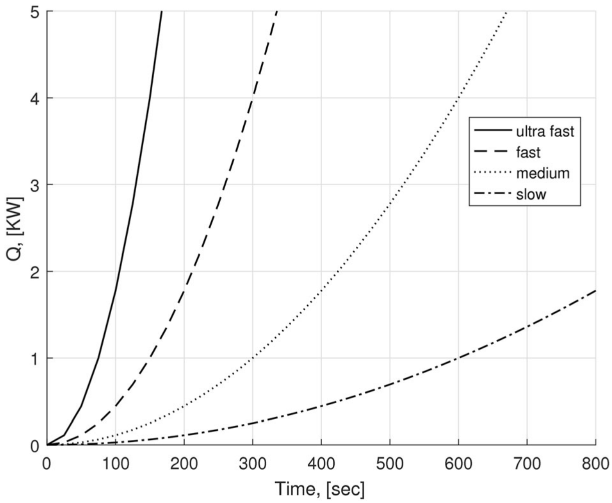

Figure 5. Fire growth curve, from the SFPE Handbook [4].

Table 4
Definition of the Fire Growth Category (FGC), According to the Properties of the Contained Materials

Type of material within the compartment	Time to grow to 1 MW (t_α)	Fire growth category (FGC)
Incombustible materials, auto-extinguishing or difficult—to—ignite (machinery, appliances, metallic objects), building materials, Slight combustible materials, distributed non uniformly or within noncombustible containers	$600 = t_\alpha$	Slow
Piled cardboard boxes, wood pallets, books on shelves, wood furniture, vehicles, materials classified for fire reaction. Slow combustible materials (typical dwellings content)	$t_\alpha = 300$	Medium
Piled plastic materials, synthetic textiles, electronic devices, combustible materials without fire reaction classification.	$t_\alpha = 150$	Fast
Flammable liquids, cellulose polymers, expanded polymers, combustible foams, not fire reaction classified.	$t_\alpha = 75$	Ultra-Fast

reference adopted here [25] has recently been considered as a source for the latest Italian Fire Code [21].

As already anticipated, the primary criteria necessary to guarantee the safety of the occupants requires RSET to be lower than ASET, and by an acceptable margin of safety. ASET obviously depends on the fire growth rate (hence on the fire growth category) and on the fire protection system. Several calculation models currently exist to simulate the movement of a crowd of people egressing a compartment where they have perceived a hazard (for example, fire). In order to evaluate ASET, it is possible to adopt fluid-dynamics-based Models, which are often time-consuming. Although the simulation of the escape path and evacuation time (travel time) were specific priorities when FSE was first introduced, many authors have recently (starting from the '90 s) focused their attention on and recognised that the time interval that anticipates the travel time plays a vital role in fire emergencies.

RSET is defined as the sum of the pre-movement time (PMT in this paper), and the movement time, which is the actual evacuation movement of the occupants. The algorithm selected by the authors to estimate PMT, which calculates the response time needed by a single occupant of a building to initiate the evacuation process in response to different evacuation procedures, was taken from the works of Marchant [22] and Sime [23].

RSET is defined, by the following equation, as the sum of five addenda:

$$\mathrm{RSET} = \mathrm{t}_d + \mathrm{t}_a + \mathrm{t}_o + \mathrm{t}_i + \mathrm{t}_e$$

where t_d is the detection time of an alarm device; t_a is the alarm triggering time; to is the occupants' response time; t_i is the occupants' reaction time; t_e is the evacuation time.

In the case in which no fire detection system is available, $t_d + t_a$ is the time needed by the personnel to detect the fire.

The approach adopted in the present model is to estimate the main contribution to RSET, the so-called pre-movement time (PMT), that is, the sum of the recognition time and the response time, as defined in [4], which corresponds approximately to the contributions of t_o and t_i, in the above equation.

The interval subdivisions reported in the SFPE Handbook are presented in Fig. 6. The yellow interval is the pre-movement time, as defined in the work by MacLennan [32], from which the FLAME approach is derived.

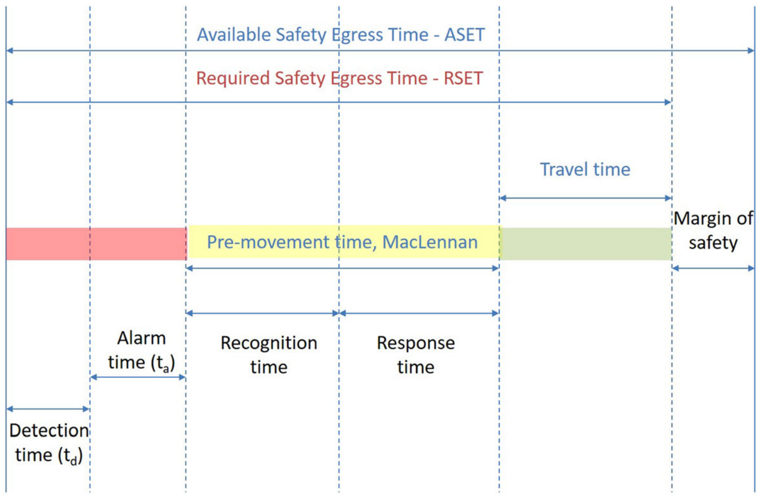

Figure 6. Definition of ASET and RSET, according to [4].

FLAME is in line with the recent Italian legislation requirements, that is, it includes the pre-movement time concept. Another method that can be used to estimate the occupants' response time may be found in the PD 7974-6:2004- and ISO TR 16738 standards, which are the sources of inspiration of the Italian Fire Code.

The approach adopted in FLAME to calculate the pre-movement time is derived from the original method proposed by Sime [23]. First, the base time (t_l) is assumed, considering three possible scenarios (Worst, Medium, Best), as a rough estimation of RSET. The base time, t_l, depends on the type of alert system that is considered; Table 5 reports the four levels of alert systems defined in FLAME. Each alert system gives a different base time, which becomes higher as the alert system becomes less efficient in signalling the event of a fire to the occupants. The Best Scenario is described in [18] as the scenario in which an effective fire emergency training of the occupants is actuated, while the worst time case is considered for the case of no training or experience.

The features of the occupants are described using seven weighted factors: three of these features are considered "key parameters", and they have a much higher weight than the others. Each occupancy typology has different priority characteristics: for example, the hospital priority features are considered 'Mobility,' 'Social affiliation' and 'Position', as they represent the reduced or inadequate capacity of hospitalised patients to escape without any help from the staff or relatives.

A modified score is obtained from the weights, according to the general law:

$$S_{\text{mod}} = 0.4 \cdot (C_n) + 2 \cdot \left(C_p\right)$$

where C_n and C_p are the values of the factors associated with the characteristics of normal and priority occupants, respectively.

An average score, W_{eff}, is obtained by dividing the modified score by the number of occupants' characteristic parameters (which is equal to 8 in this version of the model):

Table 5
Base-time Adopted in FLAME, According to [22]

Alert system	Characteristics	Base time, t_l (min)		
		Best scenario	Medium scenario	Worst scenario
A1	None, voice messages from occupants	4	7	10
A2	Manual alarm system and bell	3	5	7
A3	Pre-recorded messages and cues	2	3.5	5
A4	Live emergency evacuation directives	1	2	3

The Base-time Depends on the Alert System and on the Scenario Assumed by the Analyst (Best, Medium or Worst)

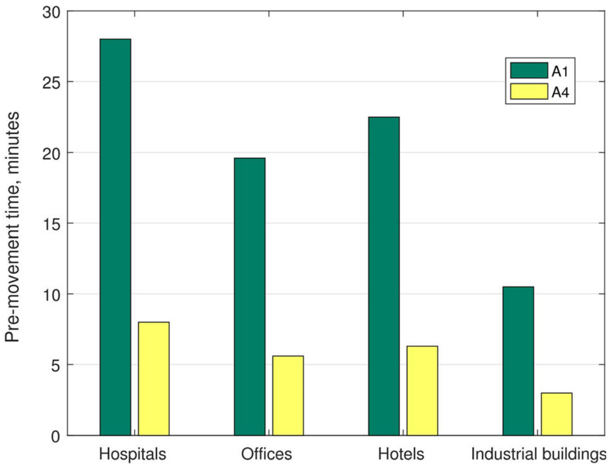

Figure 7. Example of pre-movement times for different occupancies and alarm types. A1 and A4 are the alert systems defined in Table 5.

$$W_{\text{eff}} = S_{\text{mod}}/8$$

The multiplier of base-time, t_l, is obtained by subtracting the value of W_{eff} from 6:

$$R_C = 6 - W_{\text{eff}}$$

PMT is then calculated as follows:

$$PMT = R_C \cdot t_l$$

PMT is ranked into 7 categories in FLAME. PMT depends to a great extent on the scenario, as is evident in Fig. 7. The PMT times are reported versus the alert system installed in compartments with different occupancies; A1 and A4 are defined as in Table 5.

Hospital and hotel occupancies have higher PMT values, as there are people who may be unconscious, asleep and/or unaware of fire hazards and would probably therefore take longer to recognise these fire hazards. The alert system plays a key role. Absolute values of up to more than 20 min are shown for those compartments with no fire detection and/or alarm systems installed. Smaller PMT values, which become even smaller if an advanced alert system is adopted (about 3 min, as in Fig. 6), are reported for industrial occupancy.

The occupants' characteristics are presented in Table 6, along with the definition of the range levels (1 to 5), which may, as reported in [22, 23], be described as follows: Alertness (the likelihood of occupants being awake or asleep); Mobility (sensorial and motion ability of the occupants); Social affiliation (likelihood of individuals being alone or separated from their primary social group, e.g. family, when first alerted); Role (public-to-staff ratio in the compartment); Position (likeli-

Table 6
Qualitative Description of the Occupants' Characteristic Factors in FLAME

Factor	Level 1	2	3	4	Level 5
Alertness	Asleep	People in noisy areas	People with low degree of attention (children, elderly people, psychiatrics)	People with average degree of attention	Awake with high degree of attention
Mobility	Only assisted—hospitalized	Assisted	Wheelchair-dependent	Slow (elderly people, wheelchair independent)	Normal ambulation
Social affiliation	With known people, with high degree of familiarity	Close to familiars, work colleagues	Guests of the same hotel, school	Isolated, or with people with different role (tourist, occasional guest)	Alone, isolated from known people
Role	Users with low autonomy or capacities	Occasional users	Habitual users, generic staff	Employee, medium degree of responsibility	Staff, trained employees
Position	Laying down	Sitting		Standing	Moving
Commitment	Staff, commitment-users (ticket buyers)	Users (generic), buyers (specialized shops)	Buyers (generic)	Observers, habitual passers-by	Lost or mistaken people,
Focal Point	Non focused attention (hotels, residential)	Low focused	Medium focus (buyers, workers)	Highly focused	Strongly focused (audience, spectators)
Familiarity	People with orientation issues	Occasional users, low orientation capacity	Habitual users, good orientation capacity	Habitual users	People in their workplace, homes

hood of occupants lying, sitting, standing or moving during an emergency); Commitment, that is, whether an occupant is busy finishing something, e.g. queuing to obtain a ticket, waiting to collect personal belongings, or not); Focal point (level of the occupants' attention with respect to a focal point, e.g. a theatre or cinema); Familiarity (degree of familiarity of most people with respect to the building layout, entry and exit paths).

Each of the occupants' features has a score level (from 1 to 5). Different occupancies have different scores, depending on the occupants' characteristics, as can be seen in Table 6.

The occupancy influences the estimate of the pre-movement time: Fig. 7 shows different pre-movement times obtained in different compartments with different occupancies. The alert system has a significant influence on the pre-movement time as it acts as a multiplier factor.

A particular case that has been implemented in FLAME is the "mono-compartment activity." This unusual occurrence can be defined as an activity conducted in a single compartment (no separation walls or sub-compartmentation), which is smaller than 500 m^2 and with fewer than ten people present at a time. This situation can be considered typical of small-sized commercial compartments, offices, small gathering premises or small residential buildings. In order to consider the particular features of these small activities, with respect to larger compartments, the model increases the Familiarity index, thereby accepting that the people who occupy such a mono-compartment are almost always habitual buyers, guests, workers or dwellers in their home. A higher Familiarity value than four forces FLAME to choose the Best Time Scenario (instead of Medium) and consequently reduces the pre-movement time of these particular cases.

The Ignition Probability Category (IPC) is combined with the fire growth category to obtain the exposure level to which occupants are subjected in the examined fire scenario (Table 7).

2.1.4. The Occupants' Risk Level assessment ORL is defined as follows:

ORL 1 "Minimal" areas, where few people are present and adequate evacuation paths are provided;

ORL 2 "Limited" areas, where the start of the fire may be easily discovered, and people may be evacuated with the help of the staff;

ORL 3 "Medium" areas, that is, the majority of areas where standard emergency procedures are in operation and there are people who are not capable of self-evacuating the building;

ORL 4 "Enhanced" areas, where the safe evacuation of all the occupants requires the intervention of the Fire Service;

ORL 5 "High" areas, where the safe evacuation of all the occupants may be difficult.

Table 7
Algorithm Used to Estimate the Occupants' Exposure Level (EL)

IPC/FGC	FGC1	FGC2	FGC3	FGC4	FGC5
IPC 0, IPC 1, IPC 2: Low	EL1: Very Low	EL2: Low	EL3: Medium	EL4: Enhanced	EL5: High
IPC 3 & IPC 4: Medium	EL2: Low	EL3: Medium	EL4: Enhanced	EL5: High	EL6: High
IPC 5 & IPC 6: High	EL3: Medium	EL4: Enhanced	EL5: High	EL6: High	EL6: Very High
> IPC 6: Very High	EL4: Enhanced	EL5: High	EL6: High	EL6: Very High	EL6: Very High

The scores obtained in the Fire Exposure and Pre-Movement Time calculation are combined to obtain the Occupant Risk Level (ORL) using the algorithm described in Table 8.

ORL is classified in 6 levels, ranging from 1 to 6, and a Non-Acceptable (NA) level of risk is also defined when the exposure conditions or occupants' characteristics are such that they compromise the safety of the people and no measures are able to mitigate the risk. The Italian legislation on fire safety [28] defines risk as Low, Medium or High, respectively, if: no flammable substances are present in the workplace and the structural and occupational characteristics indicate only a limited probability of fire ignition and propagation; flammable substances are present and/or the structural and occupational characteristics could favour fire ignition, but fire propagation should be considered negligible; flammable substances are present, the structural and occupational characteristics could favour fire ignition, and there is a great probability of fire propagation in the initial phase.

In FLAME, this classification corresponds to the ORL1 and ORL2 levels for Low, ORL3 and 4 for Medium and ORL5 and 6 for High.

2.2. The Property Fire Risk Chart

The property risk level (PRL) calculation accounts for different parameters from those used to estimate ORL: fire duration (which depends on the fire load); fire growth (for the occupants) up to the conditions of non-tenability of the structure, and the potential spreading of the fire effects to the neighbouring compartments; the geometrical characteristics of the source compartment; the firefighting means. The latter include fixed and mobile firefighting equipment that could reduce and mitigate the risk level by limiting the length of the fire and the possibility of escalation. The firefighting means include both active measures and passive measures. A scoring criterion is used to account for the firefighting means A score is associated with each firefighting device. The scores are summed to obtain the overall fire contrast score: the resulting value is combined with that derived from the fire severity to obtain the fire risk classification for the property (Fig. 8).

Table 8
Algorithm Used to Estimate the Occupants' Risk Level (ORL)

EL/PT	EL1: Very Low	EL2: Low	EL3: Medium	EL4: Enhanced	EL5: High	EL6: Very High
PMT1	ORL1	ORL1	ORL2	ORL2	ORL3	ORL4
PMT2	ORL1	ORL2	ORL2	ORL3	ORL4	ORL5
PMT3	ORL2	ORL2	ORL3	ORL4	ORL5	ORL6
PMT4	ORL2	ORL3	ORL4	ORL5	ORL6	NA
PMT5	ORL3	ORL4	ORL5	ORL6	NA	NA
PMT6	ORL4	ORL5	ORL6	NA	NA	NA
PMT7	ORL5	ORL6	NA	NA	NA	NA

2.2.1. Fire Length Category The fire length category is estimated considering the Effective fire load of the compartment (q_f). The specific fire load is obtained by carrying out a weighted calculation that accounts for the quantity of combustible material present in the compartment, its likelihood of participating in the fire, the containers used to store the combustible goods (which can affect the likelihood of participating in the fire) and the extinguishing devices. FLAME allows the fire length category to be estimated, via both a direct calculation (if the user knows the amount of stored combustible goods) or via the assumption of default values according to the occupancy and derived from literature data [21].

A direct calculation implies the estimation of q_f, which is mandatory in the Italian fire prevention regulations. q_f accounts for the different probability of stored materials participating in a fire and it is defined as

$$q_f = \frac{\sum_{i=1}^{n} g_i \cdot H_i \cdot \mathrm{m}_i \cdot \Psi_i}{A}$$

where g_i is the mass of the ith combustible; H_i is the lower calorific value of the ith combustible material; m_i is the fire participation factor of the ith material (0.8 for wood and cellulosic materials, 1 for others); ψ_i is the fire participation limiting factor of the ith material (0: fire-resistant container, 0.85: non-combustible container, one of any other type of container or no containers); A is the surface of the compartment.

The fire length category (FLC) is calculated considering q_f, as described in Table 9.

The Fire Length and Fire Growth categories are matched to find the Fire Severity Index (FS), which represents the strength of the fire scenario that threatens a compartment structure. Seven categories of Fire Severity can be defined according to Table 10.

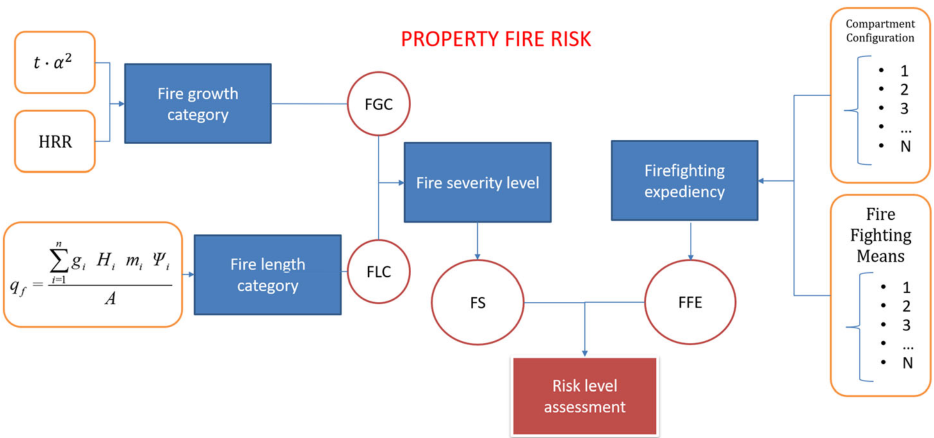

Figure 8. Property risk evaluation tree adopted in FLAME. The red circles indicate indices defined by numerical values in yellow boxes.

Table 9
Fire Length Category (FLC) Classes, According to q_f

Q_f [kJ/m^2]	Fire length category (FLC)
Qf < 900	Limited
900 < Qf < 2300	Medium
Qf > 2300	Long

2.2.2. Fire Protection Systems The ability to control a fire depends on the active and passive measures that are available at a site. Some of these depend upon the structure of the building or compartment, while others are related to environmental factors, such as building accessibility, distance from the fire brigade headquarters (which affects the expected arrival time), etc.

FLAME considers the passive (Compartment Configuration, CC), and active (Firefighting Means, FFM) measures listed in Table 11. Each variable is associated with a score, depending on its capacity to prevent or mitigate fire effects.

The base-factor (g) accounts for the size of the compartment and is proportional to the diagonal of the compartment. The other scores indicated in Table 11, depending on their nature, act as multiplying factors or addendum [13].

Active measures produce a positive effect on the fire-contrasting factor, and some have more influence than others do: automatic extinguishing systems double the score obtained for the presence of only extinguishing portable devices. In this case, a higher score means that a more effective firefighting action can be put in place.

Passive protection measures can have a positive or negative effect on the global opportunity of contrasting a fire. Accessibility is a key-element during an emergency, since the more accessible a building is (more than only one side to access it), the easier it is for the firefighters' means to approach the fire. The location of a compartment within a building affects the ability to extinguish a fire to a great extent: the higher a compartment is located within a building, the lower the probability of quickly extinguishing a fire because of the limited accessibility to firefighters and to extinguishing products (Fig. 9). Other elements, such as the

Table 10
Fire Severity Index (FS) Calculation Algorithm, Based on the Fire Growth Category (FGC) and Fire Length (FLC)

Fire length/fire growth	FLC1 limited	FLC2 : medium	FLC3: long
FGC1 slow	FS1: Very Low	FS2: Low	FS3: Medium
FGC2 moderate	FS2: Low	FS3: Medium	FS4: Enhanced
FGC3 medium	FS3: Medium	FS4: Enhanced	FS5: High
FGC3 fast	FS4: Enhanced	FS5: High	FS6: Very High
FGC4 ultra fast	FS5: High	FS6: Very High	FS7: Extra High

Table 11
Variables That Affect the Capacity to Control a Fire

Compartment configuration	Score	Firefighting means	Score
Compartment surface	$g = \frac{\sqrt{A_{tot}}}{40}$	Firefighter service	10 (Firefighting internal team) 20 (As previous with regular evacuation drills in coordination with local FF service)
Building accessibility	2*g (Only by narrow side) 0 (50% or more accessible) 2 (less than 50% accessible)	Firefighter arrival time	10 (within 10′) 7 (10′ < t<15′) 5 (15′ < t<30′) 0 (above 30′)
Compartment level	0 (Ground floor) 4 (up to 1 level higher than ground) 6 (up to 2,3 levels) 10 (up to 8) 20 (above 15th level) 12 (up to 15) 10 (underground level)	Fire detection system	20 (Automatic detection, notification and alarm system) 10 (CCTV system) 5 (manual alarm switch)
Compartment ceiling height	2 (Below 3 m) 1 (3 < h<6) 0 (above 6 m)	Extinguisher hand means	7 (Adequate number) 10 (Specialized extinguisher load, e.g. for metals) 5 (Specialized cart equipment, big size)
Fire resistance of structures	− 5 (Above 90′) 0 (Above 60′) 5 (Above 30′) 10 (Below 30′)	Hydrants	5 (Fire monitor, manual control) 10 (Fire monitor, remote control)
Emergency accessibility (protected paths, firefighters accessibility)	− 5 (Protected access paths) 5 (accessibility to FF vehicles)	Automatic extinguishing system	20 (Water sprinkler); 15 (Another extinguisher load)
		Smoke and heat vents	20 (Automatic vent system) 10 (Smoke level control, e.g. openings)
		Water supplies	10 (Internal fire water network 5 (Internal + external fire water network)

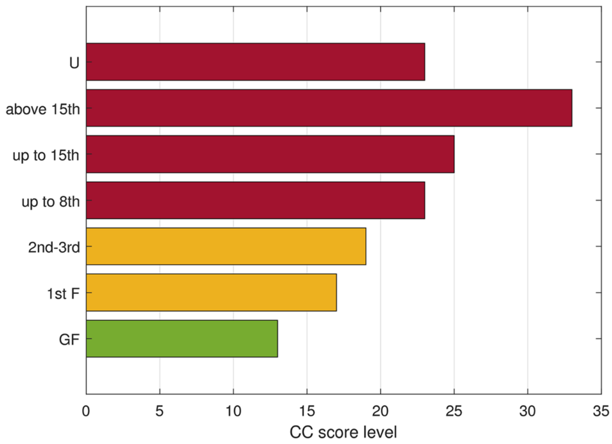

Figure 9. Influence of the compartment height above the ground (expressed in floors) on the Compartment Configuration (CC) factor.

possibility of having protected paths in the building to safeguard firefighting operations (and occupants) during an emergency or structures having higher fire resistance, to grant tenability of the building while extinguishing operations are performed, help to improve the safety measures. When a high score has been assigned to the passive measures, it means there is a reduced capacity to control the fire.

Firefighting Expediency is estimated by combining FFM and CC, as described in Table 12.

2.2.3. The Property Fire Risk Assessment The property risk level (PRL) is defined in FLAME as follows:

PRL I: damage to the structure and its contents are limited and recoverable;

PRL II: damage to the structure and its contents are probably relevant but recoverable;

Table 12
The Algorithm Used to Estimate Firefighting Expediency (FFE) from the Firefighting Means and Compartment Configuration (FFM, CC)

Compartment configuration/ firefighting means	$CC \leq 7$ Easy	$7 < CC \leq 14$ Limited	$14 < CC \leq 20$ Difficult	>20 Minimum
$FFM \geq 17$ high	FFE4 high	FFE3 medium	FFE2 low	FFE1 very low
$17 > FFM \geq 8$ good	FFE3 medium	FFE2 low	FFE1 very low	
$8 > FFM$ weak	FFE2 low	FFE1 very low		

PRL III: Relevant damage to the compartment is probable but no damage to the surrounding compartments is expected;

PRL IV: Total destruction of the compartment, as a result of fire, is probable and damage to the nearby compartments is also probable;

PRL V: A severe fire loss is likely.

PRL is estimated from FFE and FS, according to Table 13.

When FS is low and FFE is adequate, the probability of an uncontrolled fire is low, whereas if a severe condition is expected and weak firefighting measures are in place, the probability of an uncontrolled fire is high, with severe consequences and losses.

PRL is Non-Acceptable in the case where fire fighting expediency is not able to mitigate the Fire Severity, and more preventive measures are necessary to reduce the damage level.

2.3. The Protection Category Level

The FLAME method was inspired by FRA-Mini [13] and it has the purpose of defining a fire safety strategy in which a performance level is estimated.

The Technical Standards behind this approach are [14, 15]. A decisional tree is used to combine severity, occurrence probability and exposure to fire to define a risk class, without considering any available protection measures. The standard considers five risk classes [15] and indicates the protection category that is coherent with the level of risk in order to mitigate and/or reduce the risk (and the expected damage level) to an acceptable threshold value. The protection measures are divided into five performance levels, as depicted in Table 14. The different protection category levels (PCL) are defined qualitatively according to the description reported hereafter: the lowest PCL is the Base Category, which stands for "compliant with recent standards", while the highest PCL is Category 4, which considers the immediate reporting of each single failure of the components of a machine and the possibility of withstanding multiple damage as a result of emergency devices.

Table 13
The Algorithm Used to Estimate the Property Risk Level (PRL)

Fire fighting expediency/ fire severity	FS1 very low	FS2 Low	FS3 medium	FS4 Enhanced	FS5 High	FS6 very high	FS7 extra high
FFE4 high	PRL I	PRL I	PRL II	PRL III	PRL IV	PRL V	NAC
FFE3 medium	PRL I	PRL II	PRL III	PRL IV	PRL V	NAC	NAC
FFE2 low	PRL II	PRL III	PRL IV	PRL V	NAC	NAC	NAC
FFE1 very low	PRL III	PRL IV	PRL V	NAC	NAC	NAC	NAC

Table 14
Description of the Protection Category Level

Protection Category	Technical elements	Emergency plan	Maintenance
B	Fire discovery left to occupants (voice alarm)	No Emergency plan, e	protection measures under surveillance
1	Manual fire alarm, with siren	No Emergency plan, e	Periodic check of firefighting means
2	Manual fire alarm and Public address (PA) system	Emergency plan	Periodic check of firefighting means
3	Automatic fire detection and PA	Emergency plan	Ordinary maintenance, fire-fighting service, high degree of cleaning and housekeeping
4	Automatic detection and extinction of fire	Emergency plan	Preventive maintenance on firefighting means, fire drill mandatory, maximum degree of cleaning/housekeeping

FLAME assumes similar classes for PCL: from B (Base) to 4. This value depends on five aspects. The key-aspect concerns the technical firefighting system present in the compartment Table 14). The other factors pertain to the protection level obtained from the planning of emergency procedures, the fire safety management system, the implemented housekeeping and cleaning procedures and the level of maintenance and inspection of the firefighting devices. PRL level V is acceptable, albeit only when associated with PL 4, while a lower PRL may be mitigated by a lower PCL. The base category is only acceptable under particular conditions.

FLAME sets the PCL according to the Technical Elements in column 1 of Table 14. Organisational and Safety Management elements are also required to maintain the PCL defined according to the technical measures. When these are missing, PCL is downgraded to the highest value coherent with the organisational measure that is present. For example, let us consider a compartment with a manual fire alarm and a public address (PA) system. In such a case, the key-category associated with the technical measures is PCL 2. This level also requires the adoption of an emergency plan. If no Emergency Plan is adopted, the PCL is downgraded to 1 (the highest acceptable level with no emergency plan).

FLAME takes into account the Italian requirements pertaining to fire safety. For this reason, any non-conformity found when estimating the protection category level established according to the Italian standards downgrades this level to "Non-adequate".

The last step of the process consists in the assessment of the adequacy of the fire safety management system with respect to the risk level. This assessment is conducted in agreement with Italian and recent international prescriptions that require a fire safety management system. The assessment of an acceptable risk threshold is also proposed, according to the already existing fire protection measures, as described in Fig. 10 (both technical and organisational).

Four results can be obtained: Acceptable (A, green dots), where the protection measures are compatible with the risk level; Not acceptable (NA, red dots), where the protection measures may not be able to deal with the severity of the fire; Tolerable (T, red tick): where the protection measures are able to deal with the severity of fire, but improvements still need to be made; Acceptable (A, yellow dots), a particular case that deals with mono-compartment activity, as reported in Sect. 2.1.3.

As far as the property risk level is concerned, 5 degrees of acceptability are possible (Fig. 11): Acceptable (A, green dots), where the protection measures are compatible with the risk level; Not acceptable (NA, red dots), where the protection measures are not able to deal with the fire; Tolerable (T, red tick), where the protection measures meet the necessary requirements with respect to the fire, but improvements still need to be made; Improvable (I, red tick with green stars), where the protection measures are sufficient to deal with the fire, but improvements are suggested; Acceptable (A, yellow dots), a particular case which deals with mono-compartment activities, as reported in Sect. 3.1.3.

3. The Results of Case Studies

3.1. The Fire Risk Evaluation of Healthcare Facilities

The fire risk assessment of healthcare facilities raises many critical issues, as recently discussed by Fiorentini et al. [33] and by Danzi et al. [34]. The main issue is related to the particular characteristics of the occupants of these structures: a significant number of people who are unable to move and/or are dependent on staff members, connected to fixed equipment or who are unaware of the risks, such as the elderly, psychiatric patients and children. Moreover, hospitals are often characterised by a relevant complexity of the geometry of the buildings and

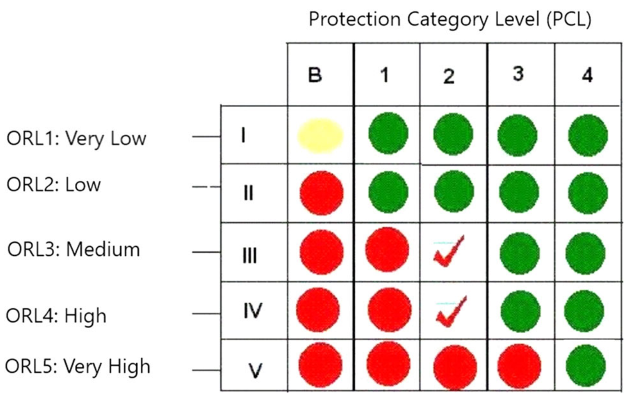

Figure 10. Acceptability criteria for the Occupant Risk Level (ORL) as a function of the protection category level (PCL).

of the compartments, as well as the vicinity of environments with a marked difference in fire load (e.g., medicine storehouses next to public access spaces).

Since the occupants of such facilities are often unaware of potential hazard signals, the internal staff members (often trained for emergencies) are in charge of managing the occurrence of fires. Staff members may discover the beginnings of a fire quickly if the structure is managed 24 h a day, even though complex structures may cause orientation problems and complicate evacuation procedures. An automatic fire-detection system, coupled with a Public Address System, would reduce the panic effect in emergencies and increase the efficacy of procedures during fire events. For this reason, health-care facilities should be equipped with a PA system or be kept under 24 h TVCC system observation to supervise compartments where there are people who are unable to evacuate a building on their own.

The particular features of the occupants of such facilities has also been reported by Charters [35], who underlined the case of patients who are highly dependent on members of staff, for example, the elderly, the mentally ill, those in intensive care units, etc. The lack of alertness, lack of mobility and high dependency on fixed equipment have obvious implications on the safety of patients in the event of a fire.

Another relevant issue concerns the fire spreading velocity, which may imply serious consequences, mainly as a result of the spread of smoke along exit paths, which can hinder the occupants attempts to reach safe locations. This fire-safety issue is particularly evident in health-care facilities, where direct communication is required between different environments. A hospital requires continuous communication between its structures and compartments. Compartmentation against the spread of smoke could be a valid safety measure, but it could be difficult to realize, for example, in the presence of an atrium, or large waiting rooms, where there are inner shafts for cables. However, in many structures, the progressive, horizontal evacuation of the occupants remains a valid emergency procedure. This process still needs well-defined and effective separations between areas on fire and safe environments close by, where the occupants who are unable to be easily evac-

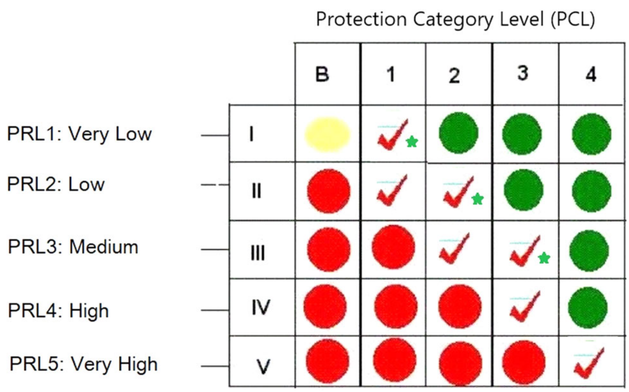

Figure 11. Acceptability criteria for the property risk level (PRL) as a function of the protection category level (PCL).

uated from a building could wait safely for firefighting rescue teams. Olsson [36] concluded that smoke-separating doors could efficiently minimise the effect of the spread of smoke and lower the consequences of a fire.

A careful and in-depth investigation should be carried out in the design-phase of healthcare facilities in order to individuate specific fire issues and to define the best fire-safety measures, according to the most probable fire scenarios, and to deal with unusual aspects and configurations of the analysed compartment. It might not always be possible to install sprinklers or automatic extinguishing systems in all of the spaces, and they might not always represent the best solution in the case of fire. However, Italian regulations (and international standards) prescribe the necessity of automatic extinguishing systems in hospital spaces where the fire load is high, such as in storehouses, laundries and laboratories.

The Swedish Rescue Service Agency collected statistics on the causes of fires in hospitals in Sweden between 1996 and 1997 [36]; 30% of the fires were due to arson, 15% to technical malfunctioning, 5% to uncontrolled smoking and 30% to unknown causes. The remaining part was due to forgotten stoves, burning candles, heat transfer, inadequate maintenance procedures and spontaneous ignition. This information, even though limited to Sweden, raises an essential point in the fire prevention study of healthcare facilities: a significant number of fires occur for unknown reasons or which are difficult to understand. This issue is related to the complexity of these structures and to the high number of factors on which a possible fire scenario is dependent. Olsson [36] defined different fire scenarios and estimated the fire risks of such facilities. The author in particular investigated in detail: a case of arson in the nursing room of a hospital; ignition due to malfunctioning of equipment in the same compartment; a fire that started in an automatic vending machine in the staff room. All these scenarios should be considered as being representative of healthcare structures.

In his work, Olsson [36] concluded that the most cost-effective way of reducing the risk of fire for people in health care facilities is to install an alarm system which alerts members of staff on adjacent wards so that they can assist in the evacuation process. Safe solutions should not depend on additional complex installations. For example, it is not advisable to attempt to compensate for an insufficient passive fire protection system for fire and smoke control with an active system like sprinklers.

As far as evacuation is concerned, previous fire episodes [36] demonstrate that occupants should preferably be evacuated through stairwells or protected paths, but in the absence of these, the firefighting team is obliged to use external ladders. In the same report, the issues related to psychiatric clinics, where exits are often locked to prevent patients from escaping, were pointed out.

Other authors have discussed and developed models to estimate fire emergency dynamics in hospitals and healthcare facilities, such as in [37, 38].

In our work, the fire risk evaluation has been conducted in different structures, including two hospitals and some doctor's surgeries, as described in Table 15, for a total of 316 compartments, with a total surface area of about 66,000 m^2.

Table 15
The Healthcare Facilities Analysed in the Present Work

Typology	#
Hospital	2
Clinic/Day Hospital	7
Family counselling service-Psychiatric help	2
Drug-dependence patients care facility	1
Technical and administrative office	2

3.1.1. Fire Risk Estimation in Clinic Visiting Compartments Such a type of compartment is frequently present in clinics, and they represent 36% of our case studies. The size of these compartments varied from a few square meters to 500–600 m^2 in the case of large areas with different consulting rooms and spaces for accessory services (i.e., cleaning service, small warehouse, nurses' office, physiotherapy room, waiting room, visiting room, etc.). A failure in an electrical apparatus is considered a low probability of ignition, while bad human behaviour (smoking) could be considered as a reasonable ignition source. These types of compartments are generally used by patients (the public) and by some of the clinic staff (medical and administrative). In general, all the occupants can evacuate the building without any external help, have discrete familiarity with the environment and, in general, are somewhat aware of the alert signals (see the values in Table 16).

The furniture in the rooms and the beds, plus some electrical apparatus (especially in dental care or cardiology clinics) constitute the typical fire loads of such buildings. The fire load is estimated from values included in the database of the method. The fire growth category is generally low, as no flammable or vast amounts of combustible materials are present in such buildings (see the values in Table 17).

Table 16
Characteristics of the Occupants Assumed to Calculate the PMT

Compartment occupancy	Clinic visiting compartments	Hospital wards	Clinics	Psychiatric ward	Warehouse
Alertness	**3**	1	**2**	**2**	4
Mobility	**3**	**1**	**1**	2	**2**
Social affiliation	**4**	**4**	4	**4**	2
Role	2	4	3	2	**5**
Position	2	**1**	**2**	2	3
Commitment	4	2	4	3	4
Focal point	4	1	1	**1**	**2**
Familiarity	2	2	4	3	4
R_C	**2.8**	**4**	**2.7**	**3.9**	**3.3**

Bold values indicate "key parameters" (see 2.1.3)

Table 17
Input Parameters of the Clinic Compartments, Where IPC Stands for Ignition Probability Category, FGC for Fire Growth Category, EL for Exposure Level, ALL for the Installed Alert system (as in Table 5) and PMT for the Pre-movement Time index

Compartment	Floor	IPC	FGC	EL	ALL	PMT
Waiting hall	G	0	1	1	A1	6
Mental Health Clinic	1	1	1	1	A1	6
Day Hospital	G	1	2	2	A2	4
Blood and samples drawing	G	1	1	1	A1	6
Warehouse	−1	0	4	4	A1	3
Drug-warehouse	−1	0	4	4	A1	4
Dressing room	−1	1	2	2	A1	5
Consulting room (prevention)	−1	1	1	1	A1	6
Consulting room (polyclinic)	1	1	1	1	A4	3
Archive	1	0	3	3	A1	4
Archive	G	0	3	3	A1	3
Utility room	G	0	1	1	A1	3
Electric generator room	−1	0	3	3	A1	4
Transformer room	−1	0	1	1	A1	3
Network cabinet	−1	0	1	1	A1	3
Cleaning storeroom	−1	0	3	3	A1	3
Electric kitchen	G	0	2	2	A1	3

The Italian Fire Code requires that each health-care facility must adopt an alarm system that is capable of warning all the occupants in all the compartments and of starting the emergency procedures. For this purpose, a Public Address network system has to be installed in each space where occupants are present, and evacuation and alarm messages should be decided on according to the fire safety management procedures, in order to be adequate and easy to understand.

Most of the compartments investigated in the clinics were not provided with a PA system. In general, the fire alarm was found to be of a manual type, with switches to turn on a siren. Such a signal has been found to result in a slow response of the occupants to the fire alarm and to increase their pre-movement time to values that imply a non-adequate risk reduction. The occupant's characteristics are listed as priority factors for each occupancy in bold in Table 16.

Lovreglio et al. [39], in their recent study on the decision–making process during pre-evacuation, focused on the behaviour of people involved in a fire emergency. They underlined how the pre-movement time, i.e., the sum of $t_o + t_i$, is the critical component of RSET and that, even in a real emergency scenario, a correlation exists between this value and the number of deaths and injuries.

The same authors continued by stating that the literature has generally focused more on the movement phase than on the pre-movement phase and that, in many cases, evacuation models adopt simplistic assumptions about the occupants' behaviour during pre-evacuation. The issue is considered and solved in FLAME through the pre-movement calculation proposed in [22]; nevertheless, this is a somewhat rough estimate, and behavioural modelling (like decision-making process modelling) is not present, as the prior aim was to build a quick tool for the evaluation of fire risks. However, further developments of FLAME could include such theories, in order to consider the occupants' response time during fires more accurately.

The Multiplier factor, Rc, depends to a great extent on the occupants' characteristics; a relevant difference in PMT is in fact obtained by varying one factor at a time (see Fig. 12). As a consequence, the time required by occupants to prepare to evacuate a building varies from 4.6 min to 23.1 min, when the Mobility Factor varies from 5 to 1 (the Mobility Factor was assumed as "priority in the calculations, see Sect. 2.1.3). Similar considerations hold if the Position Factor varies from 1 to 5, although, in this case, the lower effect on Rc (and consequently on PMT) is due to the normal weight assigned to the Position Factor.

The choice of the priority factors is critical for the risk assessment. People who are not familiar with the environment, may be present in a clinic, in consulting rooms, waiting halls or in pediatric/geriatric visiting rooms. The assumed value clearly depends on the compartment occupancy.

Some results of the risk assessment of visiting clinics are summarised in Table 18. It should be noted that, despite the very low ignition probability (IPC generally ranges from 0 to 1), several other factors contribute to increasing the risk level. The fire growth category is generally low, although it may be high in some specific compartments, such as warehouses. Nevertheless, most of the contribution to the risk level is from the high PMT, which is a direct consequence of poor detection and a lack of alarm systems. Hence, a modification of the alarm system could produce a significant decrease in the response time and an improvement in the risk level of a compartment. The risk is connected to the capacity of a fire to spread (which depends on the ignition probability and fire severity), and Table 18 therefore only applies in the case in which a fire scenario is not mitigated.

The protection measures associated with this type of compartment, which generally consist of a manual alarm system, a hydrant network and the adopted fire safety management procedures, generally results in a PCL equal to the "base" category or to 1. Combining this with a Medium risk level leads to the acceptability of the fire safety system of many of the compartments being "Inadequate" (see Fig. 10 for the acceptability criteria).

PCL should be improved to 3–4, depending on the ORL class, to meet the acceptability criteria presented in Fig. 10. PCL class 3 requires automatic fire detection systems, an emergency plan, as well as adequate maintenance and housekeeping policies (see Table 14). PCL class 4 requires, among others, automatic fire detection and suppression systems, emergency plans and preventive maintenance policies.

3.1.2. The Property Fire Risk Assessment: Clinics The Property Fire Risk is closely related to the capability of the fire to damage structures and goods. For this reason, the set of parameters is somewhat different from those used to estimate the risk to the occupants, as FLC is considered, while IPC and PMT are not

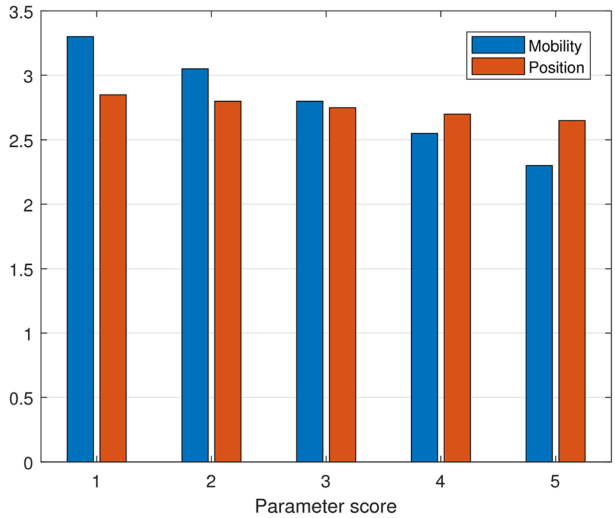

Figure 12. Effect of the Mobility and Position factor on the base-time multiplier, Rc, for clinics.

Table 18
The risk results for the clinic occupants. ORL stands for the occupants' risk level, PCL for the protection category level, NA for Not Acceptable and A for Acceptable

Compartment	Risk	PCL	FLAME result
Waiting hall	ORL5	1	NA
Mental Health Clinic	ORL5	1	NA
Day Hospital	ORL3	1	NA
Blood and samples drawing	ORL5	1	NA
Warehouse	ORL4	1	NA
Drug-warehouse	ORL5	2	NA
Dressing room	ORL4	1	NA
Consulting room (prevention)	ORL5	1	NA
Consulting room (polyclinic)	ORL2	1	A
Archive	ORL4	1	NA
Archive	ORL4	Base	NA
Utility room	ORL2	1	NA
Electric generator room	ORL4	Base	NA
Transformer room	ORL2	1	A
Network cabinet	ORL2	1	A
Cleaning storeroom	ORL3	1	NA
Electric kitchen	ORL2	1	A

accounted for. Moreover, the firefighting equipment (CC and FFM) plays a significant role in defining the PRL. The assumed parameter values for the visiting clinics are summarised in Table 19.

The main factor that affects the property fire risk is the Fire Load, as the fire damage to the buildings and structure is closely related to the total energy that the fire could deliver to the environment. The Fire Load Category (FLC), as expected, was found to have a considerable weight in many of the examined warehouses.

If the warehouses and storage rooms are excluded, the Fire Severity index is relatively low (mean value of 1.5) for all the other compartments and, consequently, a low-risk fire scenario could be expected. Nevertheless, poor acceptability results were found for these compartments, probably because of the weak firefighting measures that were adopted, as individuated by the Compartment Configuration and Firefighting Means factors. CC and FFM scored poorly in some cases, where the compartment was difficult to access or poorly protected. The consequence, in many cases, was a poor or very poor FFE score, which is the main reason for the high property risk level (PRL) observed in many of the compartments (Table 20).

FS values equal to or lower than two determine a high-risk class, but only if fewer firefighting measures have been adopted, as described in Table 19, where the maximum FFE score is 2.

An FFE score of 3 or 4 determines lower risk levels (from 1 to 3); this could be achieved with Medium scores for both the CC and FFM factors. Combined with these risk levels, a PCL score equal to or higher than three indicates an acceptable risk condition for the majority of the analysed compartments. In our analysis, a PCL of less than 3 was found for all the compartments (thus indicating the absence of automatic fire detection systems).

3.1.3. The Estimation of the Fire Risk of Hospital Compartments Hospital compartments constitute almost half of the analysed structures, but when the area percentage (m^2) is considered, the percentage rises to 57%. In the examined cases, the compartment is always larger than 400 m^2 and 50–70 people are present at the same time. The occupants are generally patients with very low mobility or are unable to evacuate the building without the help of the staff and, in many cases, the patients are in bed (possibly with severe disabilities) and less aware of emergency procedures. The emergency awareness and emergency procedures are handled almost entirely by the hospital staff. The direct consequence is high PMT classes, which peak at 7 for dialysis wards where technical reasons imply that the patients cannot be separated from the dialysis machines in less than 10 to 15 min. The mean PMT value for this type of compartment is close to 5, that is, slightly higher than Clinic compartments, due to the reasons described above.

The exposure level (EL) is somewhat higher in hospitals than in visiting clinics (see Tables 21 and 17 for a comparison), as no level 1 compartments were encountered. This higher EL level may be a direct consequence of the larger surface area of the hospital departments, which increases the IPC as the ignition rate is defined on a unit surface basis.

The risk level estimation results are summarised in Table 22. The values are high, especially for those compartments where there are patients who are unable to move (Intensive care units and dialysis wards). Hospitals generally have higher alarm and active firefighting system standards than visiting clinics. The presence

Table 19
Clinic compartment Property fire risk inputs, where FLC stands for Fire Load Category, FGC for fire growth category, FS for Fire Severity, CC for Compartment Configuration, FFM for Firefighting means and FFE for Firefighting-Expediency

Compartment	Floor	FLC	FGC	FS	CC	FFM	FFE
Waiting hall	G	1	1	1	Easy	Weak	2
Mental Health Clinic	1	1	2	2	Limited	Weak	1
Day Hospital	G		2	2	Easy	Weak	2
Blood and samples drawing	G	1	1	1	Easy	Weak	2
Warehouse	−1	3	4	6	Limited	Weak	1
Drug-warehouse	−1	1	4	4	Limited	Weak	1
Dressing room	−1	1	2	2	Limited	Weak	1
Consulting room (prevention)	−1	1	1	1	Limited	Weak	1
Consulting room (polyclinic)	1	1	1	1	Limited	Weak	1
Archive	1	2	3	4	Easy	Weak	2
Archive	G	1	4	4	Easy	Weak	2
Utility room	G	1	1	1	Easy	Weak	2
Electric generator room	−1	2	3	4	Easy	Weak	2
Transformer room	−1	1	1	1	Easy	Weak	2
Network cabinet	−1	1	1	1	Easy	Weak	2
Cleaning storeroom	−1	2	1	3	Easy	Weak	2
Electric kitchen	G	1	2	2	Easy	Weak	2

Table 20
Property fire risk results for clinics. PRL stands for the property risk level, NAC for a Non Acceptable Risk, T for Tolerable and NA for Not Acceptable

Compartment	Risk	Protection category	FLAME result
Waiting hall	PRL2	1	T
Mental Health Clinic	PRL3	1	NA
Day Hospital	PRL3	1	NA
Blood and samples drawing	PRL2	1	T
Warehouse	NAC	1	NA
Drug-warehouse	NAC	2	NA
Dressing room	PRL4	1	NA
Consulting room (prevention)	PRL3	1	NA
Consulting room (polyclinic)	PRL3	1	NA
Archive	PRL5	1	NA
Archive	PRL4	1	NA
Utility room	PRL2	B	NA
Electric generator room	PRL5	1	NA
Transformer room	PRL3	1	NA
Network cabinet	PRL3	1	NA
Cleaning storeroom	PRL5	1	NA
Electric kitchen	PRL3	1	NA

of automatic extinguishing systems and better emergency procedures leads to higher protection categories. Therefore, most of the examined departments exhibit an acceptable risk level. However, some unacceptable conditions are still found, mainly related to those compartments with a high PMT and inadequate alert system. A "superior" alert system should be installed in these compartments before they can become acceptable, or the FS value should be mitigated with measures to reduce the amount of flammable products or compensate for their presence with the adoption of fire-resistant containers. For example, a "superior" alert system (corresponding to class ALL4), with the introduction of a live-evacuation procedure, reduces the PMT of a dialysis ward from 7 to 4, that is, to an ORL equal to 4 instead of Unacceptable (NAC). This difference in PMT corresponds to a diminution of the pre-movement time value (as defined and calculated in FLAME) from 20 min to 8 min.

3.1.4. The Property Fire Risk Assessment: Hospitals The property fire risk in hospital departments is described in Tables 23 and 24. As the property risk mainly depends on the damage caused by the fire, FLC is considered. This value varies between 2 and 3 for hospital compartments (while the mean value of clinics is set at 1.5). A higher Fire Severity index is observed in hospitals than in clinics, mainly due to the larger compartment surface area, which determines larger IPC values.

Despite the FS values indicating worse scenarios for hospital compartments than for clinics, better fire safety measures have been adopted in the latter, and this leads to higher FFM scores. Only 5 to 18 compartments in Table 24 obtained a Non-Acceptable risk evaluation. This again is because of the low protection category level, which is mainly due to an inadequate fire detection system and alert devices, but also to poor fire safety management procedures, which could play a significant role in downgrading the PC level, as may be observed for the Surgical, Day-surgery and Endoscopy wards in Table 24.

4. Discussion

The results obtained from the preliminary case study presented above allow some considerations to be drawn. However, more details will be available after the extensive FLAME tests have been completed and compared with other methods.

4.1. Occupants' High-Risk Compartments

ORL classes equal to 5 or 6 indicate a high-risk level for the occupants (but also according to the Italian legal definition of High risk). The high-risk level was found for such compartments as the operating room, ICU, dialysis ward and the ER department. In this study, these compartments were all in a hospital. The high-risk level was mainly due to significant PMT values rather than to high ignition frequencies or flame diffusivity.

In general, a high-risk level is only acceptable when there is a PCL equal to 4, which implies the adoption of an automatic extinguishing system. Alternatively,

Table 21
Hospital compartments, Occupants' fire risk inputs, where IPC stands for Ignition Probability Category, FGC for fire growth category, EL for exposure level, ALL for the alert system installed (as in Table 5) and PMT for Pre-movement Time index

Compartment	Floor	IPC	FGC	EL	ALL	PMT
Technical offices	1	1	3	3	A1	3
Clinic analysis laboratory	1	1	2	2	A3	4
Odontostomatology ward	1	1	3	3	A1	4
Dialysis ward	1	1	3	3	A1	7
Radiology ward	1	1	3	3	A3	4
Endoscopy ward	1	1	3	3	A3	4
Surgery-Day Hospital	1	1	2	2	A3	6
Orthopedics ward	1	1	3	3	A3	4
Neurology ward	1	1	3	3	A3	4
Surgery block	2	1	2	2	A3	6
Pre-surgery block	2	0	2	2	A1	4
Day Surgery	2	1	2	2	A3	6
Administrative offices	2	0	2	2	A1	4
Intensive Care Unit	2	1	3	3	A3	6
Surgical ward	2	1	2	2	A3	6
Urology/otolaryngological ward	2	1	2	2	A3	6
Cardiology ward	2	1	2	2	A4	4
Nephrology ward	2	1	2	2	A4	4

ORL can be reduced by acting on its main components, that is, PMT, fire scenario or compartment characteristics (or all three). A PMT value may be reduced if an improved alert system is installed in the compartment, as in the case of a Dialysis ward which had no specific alert systems (an ALL value equal to 1); the introduction of a PA system (ALL 3) could lower the PMT value to 4 and, consequently, the ORL to 4. The mitigation of this risk level is associated with a PCL equal to 3, which implies the adoption of automatic fire detectors.

Moreover, the introduction of a live PA system could promote a decrease in the RSET and significantly reduce the fire risk to which the occupants are subjected.

4.2. Effect of Occupancy on the Pre-movement Time

The PMT value is influenced by the occupancy, according to the R_c value (base-time multiplier), which is directly correlated to occupancy factors (as reported in Fig. 13). The algorithm included in FLAME allows the PMT values to be differentiated between compartments which have slightly different occupancy characteristics, like compartments in a hospital structure.

Psychiatric wards are mainly represented by patients with a low determination ability, medium mobility, and a generally scarce attitude towards paying attention to alarms, while the dialysis ward is a particular department, where severe issues regarding emergency procedures are present. The pre-movement time of this type

Table 22
The risk results of the occupants of hospital compartments. ORL stands for the occupants' risk level, PCL for the protection category level, NA for Not Acceptable and A for Acceptable

Compartment	Risk	Protection Category	FLAME result
Technical offices	ORL3	3	A
Clinic analysis laboratory	ORL3	2	T
Odontostomatology ward	ORL4	3	A
Dialysis ward	NA	1	NA
Radiology ward	ORL4	3	A
Endoscopy ward	ORL4	2	T
Surgery-Day Hospital	ORL5	2	NA
Orthopedics ward	ORL4	3	A
Neurology ward	ORL4	3	A
Surgery block	ORL5	3	NA
Pre-surgery block	ORL3	3	A
Day Surgery	ORL5	3	NA
Administrative offices	ORL3	3	A
Intensive Care Unit	ORL6	3	NA
Surgical ward	ORL5	1	NA
Urology/otolaryngologic ward	ORL5	1	NA
Cardiology ward	ORL3	3	A
Nefrology ward	ORL3	3	A

of compartment is equal to 20 min. This estimate is based on the time required to safely disconnect patients undergoing dialysis treatments from machines, which is about 15 min.

Familiarity represents the controlling variable of PMT. Familiarity can vary significantly among healthcare facility compartments; the operating theatre and ICU are in general areas that are controlled strictly by highly trained staff who have good knowledge of the layout and emergency procedures of the premises. On the other hand, the consulting room and waiting room are typical examples of compartments where most of the occupants are occasional patients who are rarely aware of the emergency escape routes.

Warehouses, which are often dedicated to the storage of both medical records and medicine, represents a particular case. The pharmacy store of a 20,000-m^2 hospital may be considered as a typical example. The fire load in such an environment is mainly constituted by paper and plastic boxes (medicine containers). Such warehouses present the combination of a high FGC (t_α 150 s), a limited ignition source density and a non-negligible PMT (8–10 min), whose combination results in a high-ORL. The main contributor to this result is the absence of a PA system, which increases the response time to a fire emergency, even though the occupants of the compartment are trained members of staff and the characteristics of the structure are favourable for a quick evacuation.

In such cases, a PA system would significantly reduce the PMT value (to 5.8 min) and consequently the ORL value from 6 to 4.

Table 23
Hospital compartments, Property fire risk inputs, where FLC stands for Fire Load Category, FGC for fire growth category, FS for Fire Severity, CC for Compartment Configuration, FFM for Firefighting means and FFE for Firefighting-Expediency

Compartment	Floor	FLC	FGC	FS	CC	FFM	FFE
Technical offices	1	1	3	3	Easy	Good	3
Clinic analysis laboratory	1	1	2	2	Easy	Good	3
Odontostomatology ward	1	1	3	3	Easy	Good	3
Dialysis ward	1	1	3	3	Easy	Weak	2
Radiology ward	1	1	3	3	Easy	Good	3
Endoscopy ward	1	1	3	3	Easy	Weak	2
Surgery-Day Hospital	1	1	2	2	Easy	Weak	2
Orthopedics ward	1	1	3	3	Easy	Good	3
Neurology ward	1	1	3	3	Easy	Good	3
Surgery block	2	1	2	2	Easy	Good	3
Pre-surgery block	2	1	2	2	Easy	Good	3
Day Surgery	2	1	2	2	Easy	Good	3
Administrative offices	2	1	2	2	Easy	Good	3
Intensive Care Unit	2	1	2	2	Easy	Good	3
Surgical ward	2	1	2	2	Easy	Weak	2
Urology/otolaryngologic ward	2	1	2	2	Easy	Weak	2
Cardiology ward	2	1	2	2	Easy	Good	3
Nephrology ward	2	1	2	2	Easy	Good	3

5. Conclusions

A Fire Risk Assessment has always been a challenging issue for fire engineers, but it should be considered as the initial and fundamental step of a workflow aimed at defining an appropriate fire strategy. A fire strategy should be conceived considering the fire risks, and a proper equilibrium of the technical measures as well as of the organisational and management measures (among those the emergency plan and the evacuation plan of the facility). A fire strategy should be conceived on the basis of the vulnerable categories, dividing them into such categories as occupants, environment and property (including business interruptions). The Authors, moving from existing index-based methodologies, have attempted to build a method in which the fire risk can be described by a number of key attributes, while considering the fire strategy in place and the facility conditions. The resulting user-friendly tool, can be employed during the design phase of new installations and during occupational health and safety audits related to the fire risk of existing facilities. The FLAME methodology presents different workflows, in which different key parameters are considered, on the basis of the objectives: the occupants or the property. The FLAME method can be considered as a preliminary assessment tool (which can also be used during the incipient design stages), whose results may then be confirmed by a more detailed method (such as QRA).

Table 24
Property fire risk results for Hospital compartments. PRL stands for the property risk level, NAC for a Non Acceptable Risk, T for Tolerable and NA for Not Acceptable

Compartment	Risk	Protection category	FLAME result
Technical offices	PRL3	2	T
Clinic analysis laboratory	PRL3	2	T
Odontostomatology ward	PRL3	3	I
Dialysis ward	PRL4	1	NA
Radiology ward	PRL3	3	I
Endoscopy ward	PRL4	B	NAC
Surgery-Day Hospital	PRL3	B	NAC
Orthopedics ward	PRL3	3	I
Neurology ward	PRL3	3	I
Surgery block	PRL2	3	A
Pre-surgery block	PRL2	3	A
Day Surgery	PRL3	3	I
Administrative offices	PRL3	3	I
Intensive Care Unit	PRL4	3	T
Surgical ward	PRL3	B	NAC
Urology/otolaryngologic ward	PRL3	1	NA
Cardiology ward	PRL2	3	A
Nephrology ward	PRL2	3	A

FLAME workflows are based on the basic concept of risk being dependent on the magnitude of the consequences and the occurrence frequency. These are values which are connected to specific parameters that describe the fire dynamics. The parameters used to describe the fire risk are based on such descriptive fire phenomenon indices as the fire load and fire growth rate, and on indices that describe

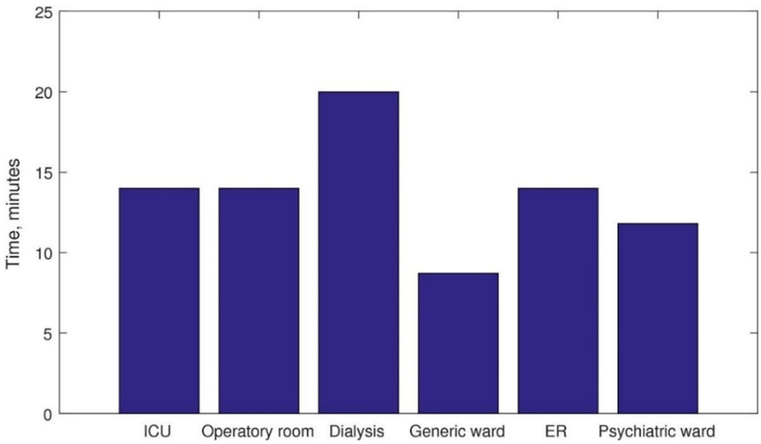

Figure 13. PMT in different hospital compartments.

the vulnerability (the occupants and property) and the maturity degree of the fire safety management system in place.

This simplified approach also allows the method to be used for audit sessions in order to analyse existing fire compartments, and to investigate whether the protection measures in force are efficient or not, or for new buildings, to optimise their fire safety protection measures. The FLAME method allows the Protection Category, which measures the resilience of the compartment to fire or to different hypothesised fire scenarios, to be determined. The Protection Categories represent the concept of the acceptability of risk, since the latter is obtained as a combination of the risk level and the protection category: the final matrix (Fig. 10, Fig. 11) shows the "acceptability" of the protection measures of a compartment adopted to "oppose" a fire.

FLAME also allows the risk to the property (business), which could be regarded as a measure of the balance between the economic losses of structures against the costs due to the implementation of fire protection equipment, to be estimated.

The FLAME approach is coherent with the current standards (Italian and worldwide) that are now moving towards a definition of the occupants' risk, in which the key factor is defined by RSET and the evacuation capability of the people inside compartments, according to their characteristics (even psychologically-dependent). The key point is that the final goal is to ensure that the occupants are able to escape safely and that the fire load only contributes to the gravity of the consequences on the structures up to their possible collapse. If this occurs, it is reasonable to presume that all the occupants have already evacuated the building, in the early stages of the fire, when tenable conditions are still present, and the fire effects (smoke, heat) do not compromise the capacity of the occupants to escape.

In the context of healthcare facilities, one of the first applications of the FLAME method was used by the authors during specific fire risk assessment phases, such as the design phase of entire facilities (e.g. new buildings); the modification of existing fire compartments and buildings; preliminary risk-based assessments conducted before further analysis with more detailed and quantitative methods during the detailed engineering phase; identification of critical issues that required further investigation, in terms of probability of occurrence and/or consequences, to gain a better insight into specific situations that the code had identified as "non-acceptable".

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