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Fire Risk Evaluation To European Cultural Heritage

European study into the Fire Risk to European Cultural Heritage

WG6

Fire Risk Assessment Methods

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Fire Risk Assessment Methods

1 Introduction

In Europe a big amount of cultural heritages exist. When referring to cultural heritage in this report we mean the historical buildings itself and also contents of great artistic/historic values inside a building. As the questionnaires in WG1 and WG2 showed a lot of fires in the past destroyed very important buildings in Europe. The results of the questionnaires showed also the lack of existing safety measures to protect the buildings in case of fire.

A fire safety system based on the normal fire codes would change the building by using other materials, fire resistant separations, ventilation systems etc. This will come in conflict with the goal of the conservationists and will need a big amount of funding. Society and/or the owner are not able or willing to pay for all fire protection measures based on the fire codes which has to be fulfilled in new buildings.

It is however obvious that more fire protection measures for cultural heritages are needed. This should be done in an optimised manner, getting an acceptable level of fire safety with a minimum of costs. For the estimation of consequences of different fires and the probability of fires one can use risk analysis methods. In literature a lot of different risk analysis methods exist with qualitative and quantitative results.

An acceptable risk analysis method in the area of cultural heritage should be used also in other areas and should have shown its ability. Depending on the occurrence of one or more intermediate event different outcomes should be available. Starting with a first event “fire” event sequences should be studied which could come to the result of different consequences. All major courses of accidents which can arise from specific events should be arranged in a convenient manner. The results of the model should provide a good framework for discussions also for non specialists. The influence of changes by single measures for the building should be seen on the result. If the principle features of the method are known, everybody can understand why certain events do occur and why other combinations of events do not occur.

In this report a short review of existing risk analysis methods will be given, discussing the advantage and also the reasons for not using certain methods in the area of cultural heritages. In five cases representative methods are described in detail including examples to allow their assessment:

- A ranking or index method called “Gretener method” with an example dealing with the Chiado fire in Lisbon,

- Another index number method called FRAME, based on the Gretener method and other similar methods, with an example dealing with a monastery used as museum,
- The Fire Risk Index Method with an example for a timber-frame multi storey apartment building.
- An event tree method with an example in a cultural heritage building.
- A probabilistic method, using the reliability index β with an example dealing with a nuclear power plant.

Finally a conclusion will be given indicating which type of risk analysis method should be used in cultural heritage. This is in line with the opinion of the group.

2 Risk analysis models

2.1 General

In overall performance management, risks are one parameter used in balancing hazards, cost, benefits and performance of an engineering system. Uncertainty is an inherent characteristic of all four parameters. In general, the balancing task mentioned involves the application of decision theory, especially decision analysis, and constitutes an engineering area of vast and expanding width. Risk will be defined as the probability of a specific undesired event occurring in specific circumstances arising from the realisation of a special hazard [1]. Fire risk is defined by ISO/PDTS 16732 [2] as

- When defined as risk of an event scenario, the combination of the probability of that event or scenario and its consequences,
- When defined as risk of a design, the combination of the probabilities and consequences of all events or scenarios associated with the design.

Every decision related to fire safety is a risk decision, whether it is treated as such or not. As the scientific understanding and the quantitative engineering tools have rapidly expanded, one cannot make fire safety decision-making process more scientific and quantitative unless new engineering tools will be placed into an appropriate fire risk analysis context. Decisions on fire risk not only requires the challenging technical steps of fire risk estimation but also requires the identification of an acceptable level of risk, which is more a task of society than a technical one [3].

Fire risk analysis is basically a structured approach to decision making, given a number of uncertainties. There are many techniques or approaches to both qualitative and quantitative fire risk analysis.

Because of the different types of risk methods there are some reasons for preferring a method and disregard a method for cultural heritages.

Acceptable features for a method are:

- people safety can be integrated in the same approach as property protection,
- the possibility to give an indication on arson,
- the possibility to have a cost estimate to risk assessment,

Reasons to disregard a method are:

- property protection is not the main goal. Methods used for people protection are less suitable as the principle that the building can be sacrificed for the safety of the people is often inherent to this approach,
- the effects to obtain an assessment should be balanced with the importance of the heritage to be protected. A method requiring a multidisciplinary team approach or a computer running during hours is not suitable for assessing risks for smaller buildings.
- cultural heritage is out of scope e.g. a method deals with explosion risks in chemical industry,
- only one organisation as owner has the right to use a method and is not accessible on a broad basis.

A generalized concept has following components [3]:

1. Identify fire hazards
2. Quantify consequence and probability of fire hazard,
3. Identify hazard control options
4. Quantify impact of options on risks of hazards
5. Select appropriate protection

By Larsson [4] methods for fire risk analysis may be classified into three categories:

- Regulations and checklists
- Ranking methods
- 0Quantitative methods

2.2 Regulations and checklists

2.2.1 General Outline

By applying regulations a satisfactory level of fire safety in a building will be achieved on a simple and safe way following the existing building codes. They have very little to do with risk assessment methods but give the easiest way of solving the fire safety problems. A number of detailed regulations have to be followed and therefore no "real" risk analysis is necessary.

Different types of checklists are often used as tools to make sure that a building fulfils the building code. Checklists can be the fastest way of identifying risk features. But it is not possible to quantify the importance of such features. Another problem is, that a useful checklist has to be developed for a special type of building, therefore different lists must be established for different types of building.

Both regulations and checklists are non-quantitative approaches and may address the steps 1, 3 and 5 from above while bypassing steps 2 and 4.

2.2.2 NFPA 914 Code for Fire Protection of Historic Structures

The NFPA 914 Code for Fire Protection of Historic Structures [5] is to be seen as a regulation based on questions like narratives. NFPA 914 contains fire protection guidelines, including the need to develop an overall fire protection plan and to emphasize the management responsibility to address fire protection and to preserve the historic integrity of the irreplaceable artefacts of historic and culture. This document gives guidance how to fulfil the regulations. Both a prescriptive approach as well as a performance-based approach is included, finding solutions to the life safety and fire safety problems in historic structures. In both cases, NFPA 914 has maintained the importance of preventing or minimizing the intrusion of the fire protection systems or solutions so as not to destroy the significance of the structure.

2.2.3 Risk Category Indicator Method

For risk assessment in cultural heritage in the NFPA, National Fire Codes [6] a risk category indicator method can be used for risk assessment and gives the answer what is to be understood by the terms high, normal and low risk. It is a type of diagnostic method in which the various elements in the building are classified in such a way as to indicate that the building in which they are found should be categorized as being high, normal or low risk.

High Risk Indicators can be elements including the following:

- Sleeping Accommodations like hotels, boarding houses, hospitals, nursing homes etc. are all high-risk buildings,
- People: The presence of people can indicate a high risk
    - o A large number of general public present in a building with which they are unfamiliar like museums and galleries,
    - o Large number of young members of the public in the building like galleries or libraries that put on special events,
    - o High density of people in the building,
    - o People are working in isolated or remote parts of the building like basements, attics, lofts etc.,
    - o High proportion of elderly or disabled people in the building like hospitals, day centres and nursing homes,
    - o There are insufficient staffing levels available to assist members of the public in evacuating the building,
- High-Risk Processes and Areas:
    - o Use of highly flammable liquids or gases, including processes such as paint spraying, solvent extraction etc.,
    - o The use of naked flames in such activities as glassblowing, metal forging or smelting etc.,
    - o The production of excessive heat by kilns, drying ovens and furnaces,
    - o The storage or use of highly flammable and/or explosive or reactive chemicals,
- High-Risk Materials: These are materials that are either easily ignited or when ignited causes the rapid spread of fire and smoke like Synthetic textiles, PUR foam, dried or artificial foliage, paints, adhesives based upon flammable solvents.
- High-Risk Structural Features:
    - o A complete lack of, or insufficient, fire resistant compartmentation,
    - o Vertical and horizontal openings through which fire, smoke and toxic gases can move,
    - o The use of non-fire-resistant glass in separating walls or in vision panels in fire doors,
    - o Wooden floors supported upon wooden joists,

- o Long and complex escape routes,
- o Large areas of flammable or smoke-producing surfaces on walls end ceilings,

Normal Risk Indicators can be elements including the following: In general, premises will fall into the normal risk category if the buildings are of conventional construction, the functional capacity, the nature or disposition of its contents are likely to present a serious fire hazard to people in the event of fire.

- A fire is likely to remain localized or at least to spread so slowly to allow people the escape,
- There is a little risk of the building or its contents catching fire easily,
- There are effective automatic systems for detecting, giving warning of fire, extinguishment or suppression of fire,
- The presence of such automatic systems allows what would otherwise be a high-risk building to be categorized as being a normal risk.

Low-Risk Indicators: There are probably very few low-risk buildings in the area of cultural heritage. An example could be an exhibition in an outdoor museum of industrial heritage or a sculpture park.

- A minimal risk to life safety,
- A negligible risk of fire occurring,
- A negligible risk of fire, smoke or fumes spreading,

2.2.4 Arson Risk Assessment Checklist

The fire protection association in the UK developed a checklist to know what the most serious fire risk is from deliberate fire to the premises [7]. Everybody even a layman can use the checklists to improve the defence of the building against arson. The checklists may be used to carry out an arson risk assessment for offices, factories, schools or health care premises. For a workplace less vulnerable to the threat of arson the answer should be "yes" to all the questions in the following checklist.

The checklist is divided in six parts, each with nearly 10 questions:

- A: Identify the external security measures
- B: Identify the internal security measures

- C: Identify the fire hazards
- D: Identify people who could start fires deliberately
- E: Identify people who could be at risk from arson attack
- F: Eliminate, control or avoid the arson threat

2.3 Ranking Methods

2.3.1 General Outline

Ranking methods or semi-quantitative methods are used in a wide range of applications. These methods have often been developed with the purpose of simplifying the risk assessment process for a specific type of building, process etc. Ranking methods remove most of the responsibility from the user to the producer of the method. But the user of a ranking method remains responsible of the data gathering but the producer of the method has narrowed his freedom of quantification. In general a group of experts first has to identify every single factor that affects the level of safety or risk, which represents positive features (increase the level of safety) and negative features (decrease the level of safety). The importance of each factor has to be decided by assigning a value. This value is based on the knowledge and the experience of experts over a long time coming from insurance, fire brigade, fire consultants, scientists etc. Assigned values are then operated by some combination of arithmetic functions to achieve a single value. The value can be called as "risk index" and is a measure of the level of safety/risk in the object and it is possible to compare this to other similar objects and to a stipulated minimum value.

Not all ranking methods include a basic level for a satisfactory protection, but give only a relative position as situation A is better/ worse/ equivalent to situation B. This can be an advantage for the user which can define his own level of protection, but in practice, most inexperienced users want that an expert system gives them a clue on "what is good enough".

An advantage of fire ranking methods is their simplicity, they are considered as very cost-effective tools. Another advantage of this method is the structured way in which the decision making is treated. This facilitates understanding of the system for persons not involved in the development process and makes it easier to implement new knowledge and technology into the system [4, 8].

In the following examples the wide range of quality is shown in the area of ranking methods or fire risk index methods.

2.3.2 Risk Value Matrix Method

For risk assessment in cultural heritage in the NFPA, National Fire Codes [6] also a risk value matrix method is proposed. This method is based on semi-quantitative terms. However, the numbers involved are purely relative, so that they have no absolute significance. The risks are made up to two elements – the probability that an event will occur and the consequences of that occurrence – the relative contributions that these two elements make to the risk can vary considerably.

The overall risk is called risk value and is defined by the simple formula as:

Risk value = fire hazard value x fire risk value

The size of the risk value becomes the basis for categorizing the building as being of high, normal or low risk. The quantification of fire hazard is done by describing it as being negligible, slight, moderate, severe and very severe and by assigning numerical values to each description from 1 to 5. In a similar way fire risks are described as being unlikely, possible, quite possible, likely and very likely and also by assigning numerical values to each description from 1 to 5. If the risk formula is applied to all possible combinations of fire hazard values and fire risk values a set of 25 numbers can be obtained. When putting all the numbers in a two-dimensional grid a risk value matrix will exist.

2.3.3 Fire Safety Evaluation System

The fire safety evaluation system (FSES) is a risk index method that was developed at the Centre for Fire Research, National Bureau of Standards in cooperation with the U.S. Department of Health and Human Services [8,9]. FSES is a schedule approach for determining equivalencies to the NFPA 101 Life Safety Code for certain institutions and other occupancies. The method treats risk and safety separately. The methodology for treating risk was developed using characteristics of a health care occupancy. The fire risk factors are patient mobility, patient density, fire zone location, ratio of patients to attendants and average patient age. Thirteen safety factors describing the building and the safety systems in the building were also selected. Each risk factor and safety factor has been assigned a relative weight from a panel of fire safety experts.

The relative risk is calculated as the products of the assigned values for the five risk factors. The expert panel also identified three different fire safety strategies like containment, extinguishment and people movement. The panel then determined which safety parameter applies to each safety strategy. The level of safety for each strategy is then calculated as the sum of the thirteen parameter values. These levels are then compared to predetermined minimum levels. The total level of safety is calculated as the sum of the three strategy values. This level is then finally compared to the level of risk.

2.3.4 Specific Commercial Property Evaluation Schedule

The specific commercial property evaluation schedule [8] is the most commonly used insurance rating schedule in the U.S. For each building a percentage occupancy charge is determined from tabulated charges for classes of occupancy modified by factors such as the specific hazards of a particular occupancy. The basic building grade is a function of the resistance to fire of structural walls, floors and roof assemblies. The building fire insurance rate is the product of occupancy charges and building grade modified by factors such as the exposure to fire in nearby buildings and the protection provided by portable extinguisher, fire alarm systems, etc.

An important concept of insurance rating is the use of loss experience. In general tabulated values and conversion factors are based on insurance calculations of fire losses.

2.3.5 Dow Fire and Explosion Index

The Dow Fire and Explosion Index (FEI) method [8] was developed by Dow Chemical to identify areas with significant loss potential. The concept of FEI is to divide a process plant into separate operations or units and consider each individually. The key aspect of the method is the identification and assessment of thermodynamic properties of the dominant combustible material in the unit. By using this approach one can identify most of the potential hazardous features. Quantitative measurements used in the analysis are based on historic loss data, the energy potential of the key material and the extent to which loss prevention practices are applied.

Material factors, general process hazard factors and special process hazards factors are used in an index schedule to derive a damage factor. The damage factor represents the overall effect of fire plus blast damage resulting from a fire or reactive energy release. The most important goal of FEI analysis is to make the engineer aware of the loss potential of each process area and to help identify ways to reduce the severity and resultant loss of incidents. The FEI has been found to be a valuable screening tool that can be used in conjunction with other analysis to help determine the relative risk and provide valuable guidance to engineering and management staffs.

2.3.6 XPS FIRE

The expert system Fire Insurance Risk Evaluation (XPS FIRE) is an example of a Ranking-Method with Checklist-Data-Input [12]. Munich Re, an insurance company, has developed the XPS FIRE for assessing the quality of industrial fire risks from a technical point of view. Their aim for this software is to contribute towards the objectivity, transparency, comprehensibility and consistency of risk assessment.

To calculate the risk-adequate premium for an individual industrial fire risk, the insurer needs information about the type of occupancy, its size, distribution of valuable objects (staff, storage of goods, machinery) and also the risk-related factors of the possible hazards. The type of occupancy is compared with existing, known types which are listed under the statistical accounts.

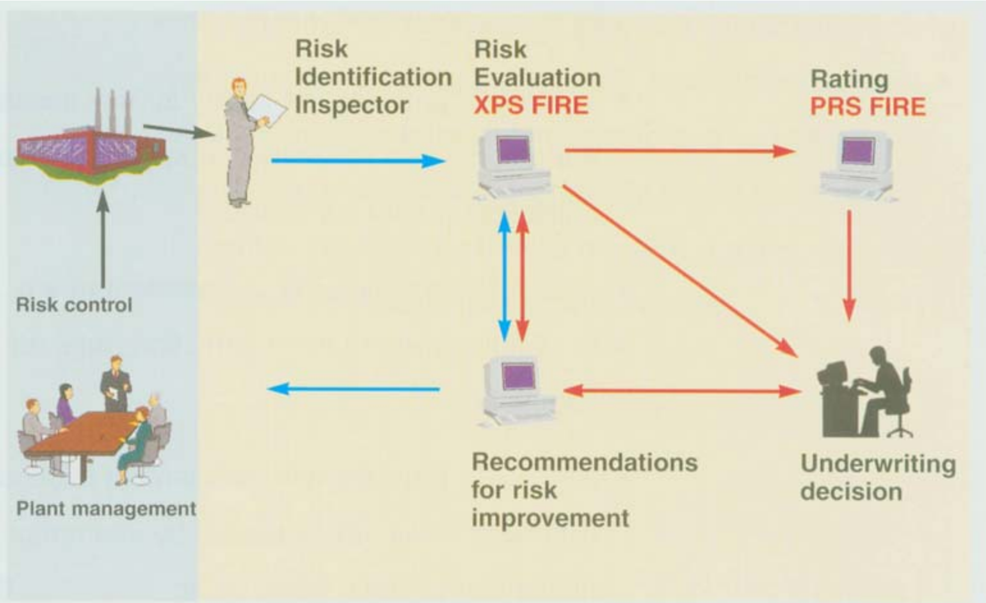


Diagram 1 Example of XPS FIRE-aided processing

Individual risk features which reduce or increase the risk determine loss expectancy in terms of probability, frequency and extent of loss. Information on these is not only required for the purpose of calculating the premium but is also crucial to the quality of the risk and for the decision of the insurer as whether and to what extent he will carry a part of the individual risk.

XPS FIRE provides the facility for risk assessment via an easy and user-friendly checklist-based input of data into the PC. This checklist enables even employees who have basic engineering experience but do not possess the relevant knowledge of all the criteria required for assessing sophisticated fire protection system to collect the necessary safety-related data on the spot, at least in less complex cases.

The input structure (necessary criteria) is built-up hierarchically:

- Construction / structural fire protection
- Occupancy hazards
  - Process hazards
  - Storage hazards
  - Supply facilities and emergency installations
- Fire Protection
  - Fire detection / alarm (manual / automatic)
  - Fire fighting
    - Fire fighting equipment
    - Water supply
    - Fire brigades
- External Hazards
- Plant safety / human element

The program uses an evaluation meter which rates the safety system from 1 to 5. With:

- 1 as the best
- 3 as a mean value which denotes the state of the art
- 5 as the worst assessment

This means that the safety systems which would generally be regarded as "good" are only graded 3 as this reflects the state of the art for the occupancy under review (Diagram 2).

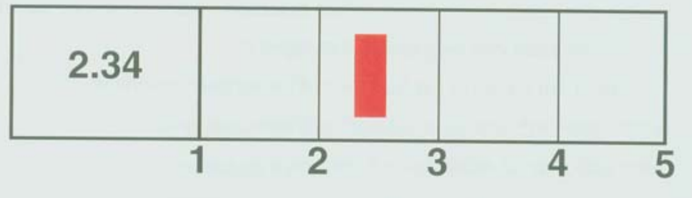


Diagram 2 Evaluation

Example: According to experts' advice, spark erosion machines in the metal processing industry must be protected by automatic extinguishing systems when operated in the automatic mode. Such systems are graded 3 in accordance with the XPS FIRE evaluation criteria.

Auxiliary installations/special hazards. The assessment does not justify a 2 or even 1 because the extinguishing system only compensates for the increased fire risk and does not raise the general level of safety.

In order to obtain an assessment even in cases where individual details are not available, the system makes realistic assumptions for this purpose. If basic answers are missing, the system calculates the less favourable alternative for the assessment to encourage the user to try again to obtain this missing information.

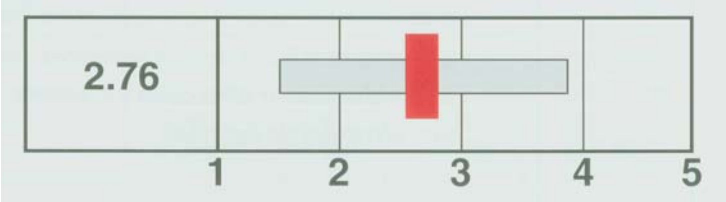


Diagram 3 Evaluation including "best-case/worst-case analysis"

The length of the grey bar (Diagram 3) is an indication of the reliability of an assessment for a given situation. As indicated above, missing information is included in the calculation by way of assumption. XPS FIRE then automatically carries out a "best-case/worst-case analysis". This means that missing information is substituted by the most favourable and also by the most unfavourable alternative and the assessment is carried out for each case. If all the requested answers are given completely in a certain situation, the evaluation meter will not show a grey bar.

This feature including the grey bar enables any user at a glance to judge the quality of information on which the assessment is based.

Risk-aggravating facilities for which no compensation whatsoever is provided by safety measures (e.g. flammable insulation where there is a risk of the fire spreading), are graded 5 and specially highlighted. This kind of individual assessment is called **k.o. criteria** (Diagram 4).

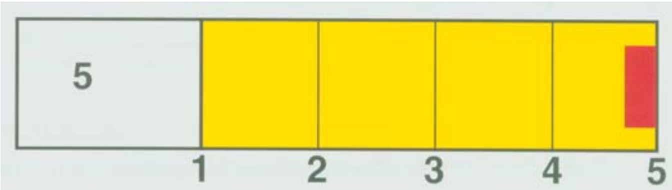
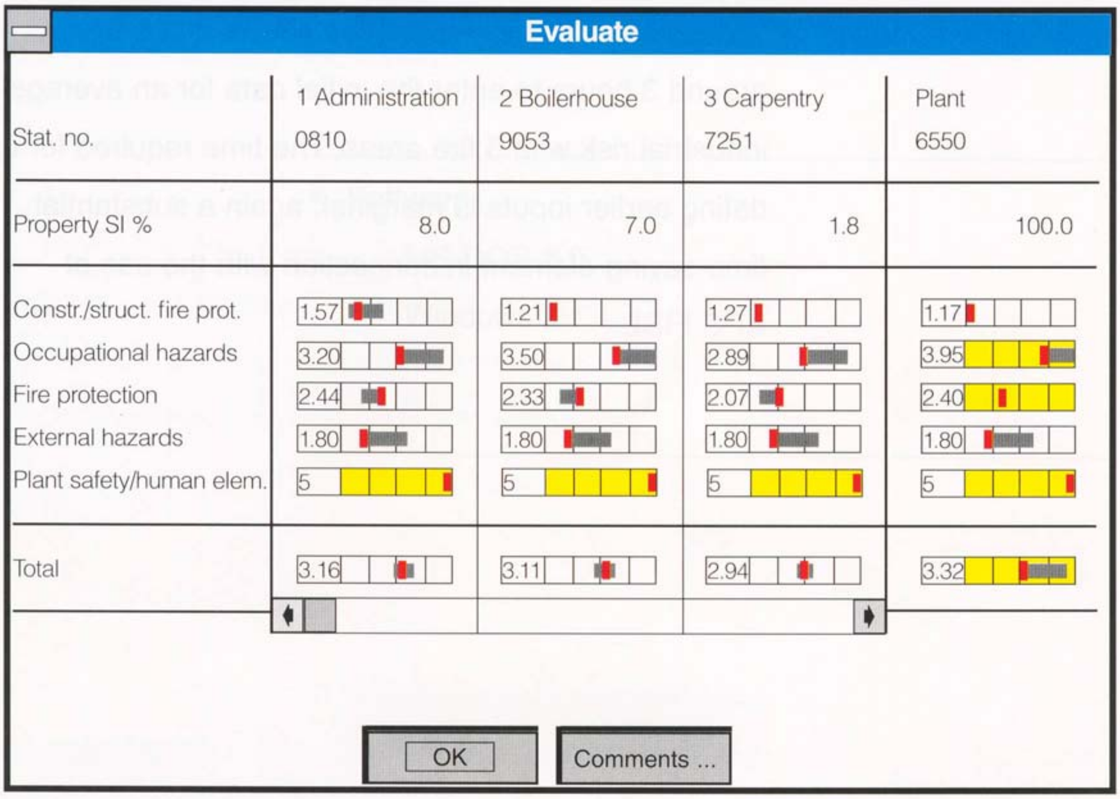


Diagram 4 Evaluation indicating **k.o. criteria**

The final assessment matrix (Diagram 5) contains the results of the five main criteria for each individual fire area. The final result or overall assessment represents a weighted average of the individual criteria results. Entering all the many detailed values creates a transparency which enables even the inexperienced user to clearly identify good features and poor features in the safety concept of a risk without the need of further assistance from a specialist.



	1 Administration	2 Boilerhouse	3 Carpentry	Plant
Stat. no.	0810	9053	7251	6550
Property SI %	8.0	7.0	1.8	100.0
Constr./struct. fire prot.	1.57	1.21	1.27	1.17
Occupational hazards	3.20	3.50	2.89	3.95
Fire protection	2.44	2.33	2.07	2.40
External hazards	1.80	1.80	1.80	1.80
Plant safety/human elem.	5	5	5	5
Total	3.16	3.11	2.94	3.32

Diagram 5 Overall evaluation

2.3.7 Hierarchical Approach

The development of a hierarchical approach to fire ranking was initially undertaken at the University of Edinburgh. Defining fire safety is difficult and often results in a listing of factors that together comprise the intent. These factors tend to be of different sorts. For example, fire safety may be defined in terms of goals and aims, such as fire prevention, fire control, occupant protection, etc. These broad concepts are usually found in the introductory section of building codes and other safety regulations. Or fire safety may be defined in terms of more specific hardware items, as combustibility of materials, heat sources, detectors, sprinklers, etc. These topics are more items listed in the table of contents of building codes. A meaningful exercise is to construct a matrix of fire safety goals versus more specific fire safety features. This matrix will help to identify the roles of these two concepts [8].

Usually there is a need for more than two levels in the hierarchy of fire safety. In practice five different “decision making levels” have been used.

Table 1: Hierarchy of fire decision-making levels

Level	Name	Description
1	POLICY	Course or general plan of action adopted by an organisation to achieve security against fire and its effects
2	OBJECTIVES	Specific fire safety goals to be achieved
3	STRATEGIES	Independent fire safety alternatives , each of which contributes wholly or partly to the fulfilment of fire safety objectives
4	PARAMETERS	Components of fire risk that are determinable by direct or indirect measure or estimate
5	SURVEY ITEMS	Measurable feature that serves as a constituent part of a fire safety parameter

Examples that might be found on each level of the hierarchy are:

- Objectives – Life safety
- Strategies – to provide safe egress
- Parameters – Detector system
- Survey Items – Type of detectors

Once the levels of the hierarchy have been identified the parameters in each level have to be specified. The parameters, especially for the lower levels have to be specified for every type of building.

In the next step each parameter in a level has to be expressed numerically in terms of the parameters in the immediate lower level using a weight which is expressed on a scale from 0 to 5. In most applications the Delphi technique is used for these rather subjective judgements. A group of experts is asked to rank fire safety objectives with respect to their importance to policy. Each member of the Delphi group receives feedback in the form of response averages, and the process repeats until an acceptable level of consensus is reached. The Delphi exercise yields a vector representing the relative importance of each objective to policy. The Analytical Hierarchy Process (AHP) is another suitable technique. This process can be unstable when there are more than six or seven factors to be ranked [8].

In order to facilitate mathematical manipulation the values of the matrices can be normalized. The Objective x Policy vector is multiplied by the Strategies x Objectives matrix to give the Strategies x Policy vector. This is then multiplied by the Parameter x Strategies matrix to finally give the Parameters x Policy vector. Details of this procedure are shown in [13].

Matrices cannot describe the influence of Survey Items on the Parameters. The relationships between the Parameters and their Survey Items have to be formulated separately for each parameter.

The final result of the matrix manipulation is a vector, describing the overall Fire Safety Policy in terms of all the Parameters. The received risk index may be calculated according to

$$S = \sum_{i=1}^{n} w_i x_i$$

where S = risk index expressing the fire safety

n = number of Parameters

w_i = weight of Parameter i

x_i = grade for Parameter I

The weights are usually normalized as:

$$\sum_{i=1}^{n} w_i = 1$$

The risk index receives a value between 0 and 5 and can be compared either to another building or to a predetermined minimum value.

2.3.8 SIA 81 – Gretener Method

SIA 81 is a Swiss risk assessment method developed by Max Gretener [10] and has been revised a number of times. The basis is that determining fire risk by statistical methods based on loss experience had to be complemented by a more rapid alternative. This method is well accepted in Switzerland as well as in several other countries [11]. It has been recommended as a rapid assessment to evaluate the fire risk of alternative concepts for large buildings. The method is one of the most important fire risk ranking methods because of its acceptance for insurance rating and code enforcement.

The Gretener method is used to evaluate and compare the level of fire risk of alternative concepts by grading the elements of a building and their performance. The grading factors are claimed to be based on expert knowledge, a large statistical survey and tested by a wide practical application. The calculated risk is compared to the accepted risk, where the latter is a function of the mobility of the persons involved and of the location of the relevant fire compartments within the building.

The approach begins with the explicit concept of risk as the expectation of loss is given by the product of hazard probability and hazard severity:

$$R = A \times B$$

with: R = fire risk

A = probability of fire occurrence

B = fire hazard, degree of danger or probability severity

The method is based on these two probabilities and combines them in accordance with probability theory [8] as

$$\text{Fire Hazard} = \frac{\text{Potential Hazard}}{\text{Protective Measures}}$$

That is :

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

with: P = potential hazard or "potential danger", which is a function of the building and its contents that influence fire ignition and spread of fire

N = "normal measures" like fire extinguishers, fire hydrants, trained personnel,

S = "active measures" like fire detection, alarm, type of fire brigade, sprinkler, smoke and heat vents,

F = "passive measures" like supporting structures, surrounding walls and ceilings, sizes of fire compartments,

P as "potential danger" is a function of the building and its contents that influence fire ignition and spread of fire and can be written as:

$$P = q \times c \times f \times k \times i \times e \times g$$

Content: q = fire load
c = burning behaviour
f = smoke production
k = content of corrosive agents in the smoke

Building: i = fire load in building construction
e = storey, basement, storage height
g = size of fire compartmentation, ratio between length and width

As with most other index approaches the values for these individual factors are not based on statistics but are empirical figures resulting from a comparison of analyses of fire risks for which fire protection measures are either common or required by law.

The acceptable fire risk value for a building is defined as

$$\gamma = R_u / R$$

with R_u as acceptable risk
R = fire risk in the building

The value of acceptable risk is:

$$R_u = 1.3 \times p_{H,E}$$

$p_{H,E}$ is the fire risk to persons depending of the type of building with values between 1 to 3. The fire risk is acceptable if $\gamma > 1$.

In Annex A an example is given for use of this method for the Chiado fire in Lisbon in 1988.

2.3.9 Fire Risk Assessment Method for Engineering

For the Fire Risk Assessment Method for Engineering (F.R.A.M.E) De Smet [14,15] described in detail the scientific background, the definitions and the basic formulas for this method. F.R.A.M.E. is a comprehensive, transparent and practical calculation method for fire risks in buildings. It is a tool to help a fire protection engineer to define a sufficient and cost effective fire safety concept for new or existing buildings. Unlike building codes that are mostly meant to assure a safe escape or rescue for the occupants. F.R.A.M.E. also aims at protecting the building, its content and the activities in it. This method can easily be used to evaluate fire risks in existing situations, and to find out whether alternative designs also have comparable efficiencies.

The F.R.A.M.E. method calculates the fire risk in buildings for the property and the content, for the occupants and for the activities in it. A systematic evaluation of all major influence factors is given, and the final result is a set of values which express in numbers what otherwise has to be said by a long description of positive and negative aspects. The method is not suitable for open-air installations.

F.R.A.M.E. is developed from the Gretener method and from various other similar approaches.

The Gretener-method was originally made for the property fire risk. Some reports of fires with minor property damage but with fatalities indicated a need for a similar but distinct approach for human fire safety. Consequential loss or business interruption is a third aspect of fire risk that is considered in F.R.A.M.E., following the same reasoning as for the property and life safety.

The method is based on empirical formulas and a large professional experience of several persons. Although it is not possible to proof the method by actual fire tests, F.R.A.M.E. has been frequently checked on real case studies. De Smet gives the following example:

a) For a series of buildings that are considered by experts to be well protected, the calculated values indicate also well protected buildings.

b) For a series of real building fires, which have been described in detail in the professional press, the calculated values indicate the same weak points that became evident by the real fires.

c) The balance of influence factors that is used in F.R.A.M.E. is comparable to what is found in most international fire codes.

In annex B the structure of F.R.A.M.E. is given in detail including a scientific “background”. For illustration the method is applied to a historic building - a 13th-15th century monastery used as Museum and Cultural Centre [16].

2.3.10 The Fire Risk Index Method

The Fire Risk Index Method is a well accepted tool in the Nordic countries and is used by Larsson [4, 17, 18] for a timber-frame multi-storey apartment building. The Fire Risk Index Method is aimed to be easy to use also for persons without deeper knowledge about fire safety. The user has to be familiar with the building regarding e.g. drawings, construction solutions, materials and the design of the ventilation system. When the level of fire safety also includes the possibility of an effective rescue, knowledge about fire services has to be included.

The Fire Risk Index Method can be applied to all types of ordinary apartment buildings. A high risk index for buildings represents a high level of fire safety and a low risk index a low level of fire safety. The theoretical value is from 0.0 to 5.0. Different decision levels are presented: Objectives, Strategies and Parameters. Seventeen possible Parameter grades are calculated by using grading schemes. When applying The Fire Risk Index Method to an apartment all 17 grading schemes have to be used. The final risk index will be calculated including all 17 Parameter weights and grades by

$$S = \sum_{i=1}^{n} w_i x_i$$

with S = risk index expressing the fire safety in the building

n = number of Parameters (= 17)

w_i = weight of parameters I

x_i = grade for Parameter (found in grading schemes)

In annex C the structure of The Fire Risk Index Method is shown. To illustrate how The Fire Risk Index Method may be used, in annex C it has been applied to a reference object. In the last table of annex C the index calculation is given for the timber frame apartment building as an example.

2.3.11 Application of ranking methods

The following table gives an overview on the different ranking methods mentioned above and their ability to meet the acceptance criteria, reasons to disregard the method or positive features of the method.

Table 2: Application of ranking methods

method	meets the criteria	negative features	positive features
Risk Value Method	no: Does not meet the “select protection” step		
FSES	yes	is not aimed at property, but at life safety	
CPES: Commercial Property Evaluation Schedule	yes		cost of insurance
Dow Fire and Explosion Index	yes	cultural heritage is out of the scope	
XPS FIRE	yes	owned by Munich Re	
Hierarchical Approach	yes	Workforce requirement: Delphi group	
SIA 81 (Gretener)	yes		insurance premium related
FRAME	yes		life safety and business risk included, insurance premium related, arson clue
FRIM: Fire Risk Index Method	yes		easy to handle

2.4 Quantitative methods

2.4.1 General Outline

Probabilistic methods are the most informative approaches to fire risk assessment in that they produce quantitative values, typically produced by methods that can be traced back through explicit assumptions, data and mathematical relationships to the underlying risk distribution. Magnusson [19] suggests that there are two primary approaches to risk analysis:

- The single scenario, analytic safety index β approach and
- The multi-scenario, event tree approach (ETA).

Because of the complexity of ETA-based risk analysis, computer are often used to enable multiple scenarios to be evaluated in a relatively short time frame. In the following section different types of quantitative methods will be introduced.

2.4.2 CRISP

CRISP (Computation of Risk Indices by Simulation Procedures) is a complete “system” model of fire scenarios, including people movement and behaviour [20]. Fire is currently limited to a single item (although an 'item' representing full room involvement could be defined). Fire growth is either a t-squared curve, modified for max flame cone radius, radiation feedback, vitiation, fuel or one can use predetermined HRR curves (e.g. from furniture calorimeter). Production of combustion products depends on oxygen availability (plume equivalence ratio). Smoke movement is calculated using a 2-layer zone model. Ionisation- and heat-detectors are modelled, also sprinkler heads (on activation the fire is suppressed by following an exponential decay).

People are aware of their surroundings (see smoke / hear alarms or warnings or reassurance from other people / feel heat / experience breathing difficulty) and this influences their decisions. The behaviour is described by sequences of actions; each action requires a person to go to an appropriate room, followed by a waiting period when the destination has been reached. Conditions encountered en route may cause the current action to be changed for something more suitable. Route choice is done by considering the building geometry as a network of rooms linked by vents - the route with minimum degree of difficulty (DOD) is chosen; if two or more routes with equal DOD exist, the shortest is selected. Movement within each room, to the next vent on the route (or the end point if in the final room of the route) is governed by 'contour maps' of distance to go. People move in order to minimise the distance to go, however they will try to avoid grid cells that would cause them to slow down (due to the crowd density of people already in that cell) in order to maximise the rate at which distance to go is decreased. The 'contour maps' of distance (and the associated direction cosines of the optimum path) can account for any obstructions in the room, and enable people to avoid them.

The model attempts to calculate pre-movement time (rather than use an empirical distribution) in terms of the time delays associated with various actions performed by the occupants in response to the early fire cues. Then the occupants may perform a number of actions (e.g. investigate, warn others) before actually starting to escape. People never 'panic'.

As the people move around, they are exposed to smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is assumed to be 'dead'. The risk is expressed simply in terms of the fraction of people originally present who end up 'dead', averaged over a sufficiently large Monte-Carlo sample.

The stochastic aspects of the Monte-Carlo are mainly concerned with the starting conditions, e.g. the type of fire item, room of origin, whether doors/windows are open/closed, how many people are present, what their attributes are (occupation, behavioural role, movement speed, head height), their location, whether awake, etc.

2.4.3 Risk-Cost Assessment Model

FiRECAM (Fire Risk Evaluation and Cost Assessment Model) is a user-friendly computer program that can be used to assess the level of fire safety that is provided to the occupants in an apartment or office building by a particular fire safety design [20, 21]. As well, the model can assess the associated fire costs that include capital and maintenance costs of the fire protection system and expected fire losses.

FiRECAM can help to identify whether a proposed design meets the life-safety performance required in a performance-based code, or is equivalent in life-safety performance to the implied life-safety performance of a code-compliant design as specified in a prescription-based code. This allows a designer to identify cost-effective fire safety designs that provide the required level of fire safety.

FiRECAM calculates the Expected Risk to Life (ERL) of the occupants and the Fire Cost Expectation (FCE) in a high-rise apartment or office building as a result of a set of probable fire scenarios that may occur in the building. To undertake the evaluation of life risks and fire costs, FiRECAM simulates the ignition of a fire in various locations in a building, the development of the fire, smoke and fire spread, occupant response and evacuation, and fire department response. These calculations are performed by a number of sub-models interacting with each other. There are nine sub-models that are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from a set of probable fire scenarios that may occur in a building. The computer model also includes three optional sub-models that can be run if the building fire characteristics and fire department response are not considered typical or if costs caused by a fire hazard are required. One sub-model is run only once to obtain the failure probability values of boundary elements. FiRECAM is the only comprehensive model in the world that includes the probability of fire spread in a building, the response of the fire department and the estimate of fire costs, in addition to the typical modelling of fire growth, smoke spread and human response and evacuation.

FiRECAM uses statistical data to predict the probability of occurrence of fire scenarios, such as the type of fire that may occur or the reliability of fire detectors. Mathematical models are used to predict the time-dependent development of fire scenarios, such as the development and spread of a fire and the evacuation of the occupants in a building. The life hazard to the occupants posed by a fire scenario is calculated based on how quickly the fire develops and how quickly the occupants evacuate the building in that scenario. The life hazard calculated for a scenario multiplied by the probability of that scenario gives the risk to life from that scenario. The overall expected risk to life to the occupants is the cumulative sum of all risks from all probable fire scenarios in a building. Similarly, the overall expected fire cost is the sum of fire protection costs (both capital and maintenance) and the cumulative sum of all fire losses from all probable fire scenarios in a building.

2.4.4 The Building Fire Safety Engineering Method

The Building Fire Safety Evaluation Method (BFSEM) is another approach to identifying hazards and consequences, and for obtaining judgments on the likelihood of events occurring [21]. The BFSEM is a structured framework for evaluating building fire safety performance that can be used for hazard assessment or risk analysis. With this method, the user can evaluate the likelihood of ignition, fire growth, and fire spread through an existing building or new building for which plans have been developed, focusing on such factors as fuel loading, occupancy characteristics, active fire protection features, and structural features. Using network diagrams, the user evaluates such factors as ignition potential, fire growth potential within the compartment of origin, and occupant safety. The user can assign subjective probabilities, based on experience and engineering judgment, or statistical data when available, to estimate the likelihood of each event occurring (the outcome is the likelihood that any event will or will not occur). A network diagram is shown in Figure 1.

With the BFSEM, building fire safety performance is evaluated using experience and judgment regarding how fire will develop and spread considering fire-related factors such as fuel load and arrangement, and fire-protection features such as automatic and manual fire detection and suppression, barrier integrity, and emergency systems. When desired or required, experience and judgements can be supported by deterministic calculation methods.

In attempting to determine the likelihood of successful control of a fire by sprinkler activation, for example, one must evaluate the ability of the fire to grow to a sufficient size to activate the sprinkler and then evaluate the likelihood that the sprinkler can control the fire. The latter action may involve an evaluation of the sprinkler system (or design), the water supply, and the reliability of the system operation (statistical data, when available, can be added to support this stage of the evaluation).

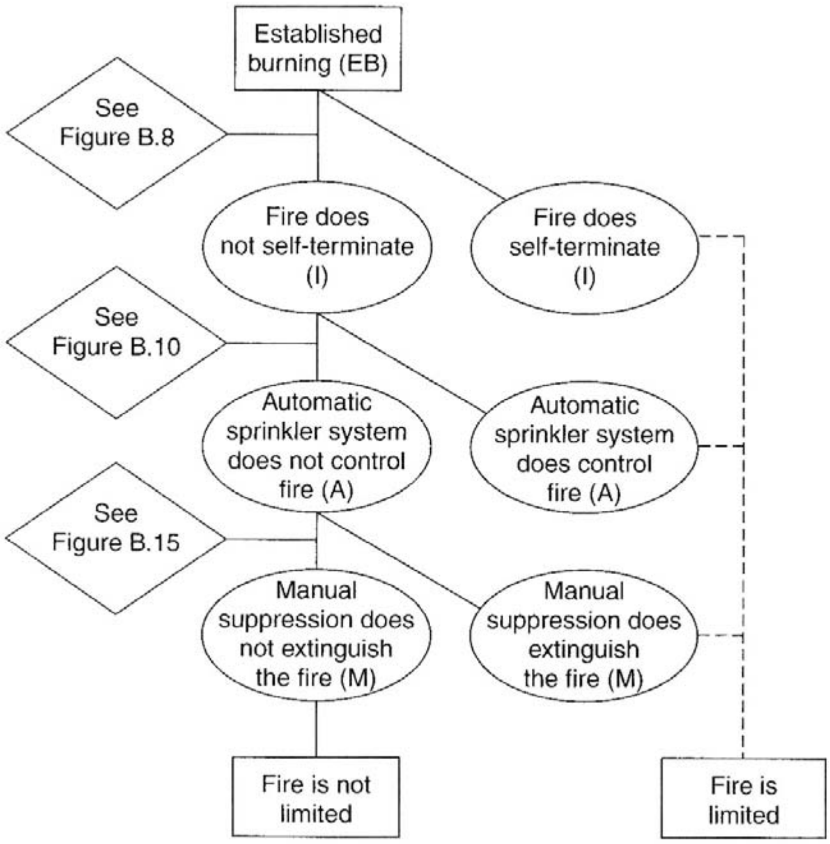


Figure 1: Example of BFSEM network diagram

2.4.5 Fire Evaluation and Risk Assessment

FIERAsystem (**Fi**re **E**valuation and **R**isk **A**ssessment) is a fire risk assessment model for evaluating the risk from fires in light industrial buildings, such as warehouses and aircraft hangars [4, 20]. The model uses deterministic calculations of selected fire scenarios to evaluate fire development, smoke and fire spread through a building and occupant response and evacuation. The behaviour of the building elements to the fire attack is considered to determine the time for the fire to spread from the fire compartment to the adjacent compartments. Also, fire department response and effectiveness, as well as reliability and effectiveness of the different active fire protection systems including detectors and automatic suppression systems are considered in the analysis.

Following the deterministic calculations, the model calculates time dependent probabilities of death based on the conditions in each compartment. Parameters considered for these probabilities include thermal radiation heat flux, concentration of toxic gases and temperature of hot gases in the compartment, all of which are computed deterministically by the FIERAsystem submodels. The probabilities of death are then used to determine the number of people that may die using the residual population, which is computed by the occupant response and evacuation models.

FIERAsystem also calculates the expected fire losses for each scenario based on the type of contents and their sensitivity to fire, smoke and water and the heat fluxes and smoke concentrations in each compartment. Knowing the expected losses for each scenario and the life risk, enables the selection of cost-effective fire safety designs.

In addition to evaluating the risk from fires, the model can also be used to determine compliance with established objectives based on criteria selected by the model users. This feature makes FIERAsystem a particularly useful tool for fire protection designers working in a performance-based code environment.

2.4.6 Petri net to Fire Safety Analysis

A probabilistic approach to the analysis of fire safety in hotels was developed by CSTB and CEP (Contrôle Et Prévention) in 1986-1992. The objective was to develop a method and a tool to evaluate the probability of multiple victims of an accidental fire starting in a bedroom. The expression "multiple victims" means here that the unwanted final event is finding dead people not only in the initial fire room, but also in other locations in the hotel. The lower the probability of this critical event, the higher the fire safety level.

The probabilistic tool used to obtain the probability of multiple victims was a temporized stochastic Petri net. Petri nets are utilized since 1985 in several fields of application, e.g. in risk analysis of plants, or in scheduling of projects [36,37].

A short description of the kind of Petri net used in this work can be given in the following way:

- A Petri net consists of four sets of objects: places, transitions, arcs and messages.
- Places represent the basic possible states of the various components of the system. For example, a place corresponds to the death of people in the corridor of the fire level. A certain number of particular places are active at the start of the simulation and other

places, more numerous, are non-active initially. "Tokens" are used to demarcate the set of places. An active place is characterized by one or several token(s) placed on it. When a place is active its variable state is true. The global ensemble of places marked at any given time defines the state of the system at this time.

- Transitions correspond to events the occurrence of which changes the marking of the network.
- Logic and graphic representation consists in linking together certain places and transitions using valuated arcs, which diagrammatically represent possible fractions of scenarios. The valuation of weight of the arc indicates the number of tokens associated with crossing the transition to which it is leading.
- Crossing a given transition is possible if the two following conditions are satisfied:
    - o The entrance places must be marked with the necessary number of tokens. For example, if the weight of the upstream arcs is 1, crossing the transition is accompanied by the removal of one token from each upstream place. A token is then added to each place linked to the transition by a downstream arc given a value of 1.
    - o The messages associated with the upstream arcs must have the required Boolean values.

      At this step, the transition is said to be valid. In a temporized Petri net as used for fire safety, a third condition to the triggering of the transition is a crossing delay : after the two previous conditions are satisfied, crossing the transition needs some time.
    - o The delay of a given transition is described by a probability density function (PDF) provided by an expert. At each activation of a transition a particular value is given the delay from a random run of the PDF. This possibility leads to different possible scenarios with the same given set of initial conditions and can then simulate a number of fire evolutions generated by Monte-Carlo simulation, each of them leading to a certain number of victims.
    - o This result either in withdrawing token(s) from the upstream place, or adding token(s) to the downstream place. The messages are Booleans which take on a True or False value. They are used so that crossing the associated transitions which appear in the different parts of the network can be synchronized or made possible. Crossing certain transitions is accompanied by the issuing of a change in the Boolean value of certain messages: as a

result, certain other transitions, frozen up until then, become valid. The initial state of the messages (True or False) has to be given before the simulation.

Places, transitions, weight of arcs, messages and PDF of delays are given in the "events model" build by an expert in fire safety. The Petri net software generates the fire histories that are possible according to the given representation and rules.

The model takes into account the presence and operation, or the absence or non-functioning, of detection, alarm and smoke control equipment. It also incorporates several features of the human behaviour and evacuation.

A number of runs have been executed, giving a prevision of the number of multiple victims for different sets of fixed initial conditions and all the histories generated from each set of initial conditions. The results can then be used to evaluate both the risk of death with e.g. given equipment and the efficiency of a change in this equipment.

As far as we know, this work or a similar one was not continued in the fields of Fire Safety, maybe because of the skill necessary to develop the model in a readable way, the difficulty to justify a unique design of places and transitions and to develop the associated Petri net, and the amount of work implied in running them and analysing the results. Automation of the building of computer codes with new languages and, in general, the dramatic increase of computer capabilities should authorize a new application of Petri nets in FS in the next future.

2.4.7 Probabilistic Methods

Probabilistic methods are the most informative approaches to fire risk assessment in that they produce quantitative values. They can be divided into four different types [3]:

- **Event tree:** An event tree is a graphical logic model that identifies and quantifies possible outcomes following an initiating event. The tree structure is organized by temporal sequence [22]. Probabilities can be calculated from the tree, and consequences are typically assigned to the end states but may cumulate along the tree. A detailed description of the method will be given in chapter 2.4.7.

- **Fault tree:** Fault-trees provide a relatively simple graphical notation based around circuit diagrams [23, 24]. They are, typically, used pre hoc to analyse potential errors in a design. They have not been widely used to support post hoc accident analysis. They do, however, offer considerable benefits for this purpose. The leaves of the tree can be used to represent the initial causes of the accident. The symbols in Figure 2 can be used to represent the ways in which those causes combine. For example, the combination of operator mistakes and hardware/software failures might be represented using an AND gate. Conversely, a lack of evidence about user behaviour or system performance might be represented using the OR/XOR gates. Basic events can be used to represent the underlying failures that lead to an accident. Intermediate events can represent the operator 'mistakes' that frequently exacerbate system failures. An undeveloped event is a fault event that is not developed further, either because it is of insufficient consequence or because information is unavailable. This provides a means of increasing the salience of information in the notation. Less salient events need not be developed to greater levels of detail.

There are a range of important differences that distinguish the use of accident fault trees from their more conventional application. Fault trees are constructed from events and gates. However, many accidents are caused because an event did not take place. These errors of omission, rather than errors of commission typify a large number of operator 'failures'.

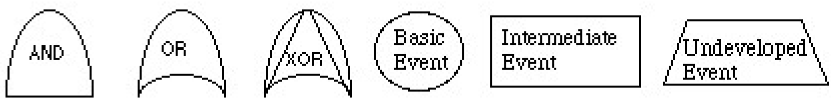


Figure 2: Symbols for Fault Trees

A fault tree is similar to an event tree in that it starts with an event, but instead following the consequences, it traces the causes. Figure 3 presents an example fault tree for the sprinkler system. It begins with the problem we wish to analyse, known as the top fault or event, which in this case is the sprinklers failing to extinguish the fire.

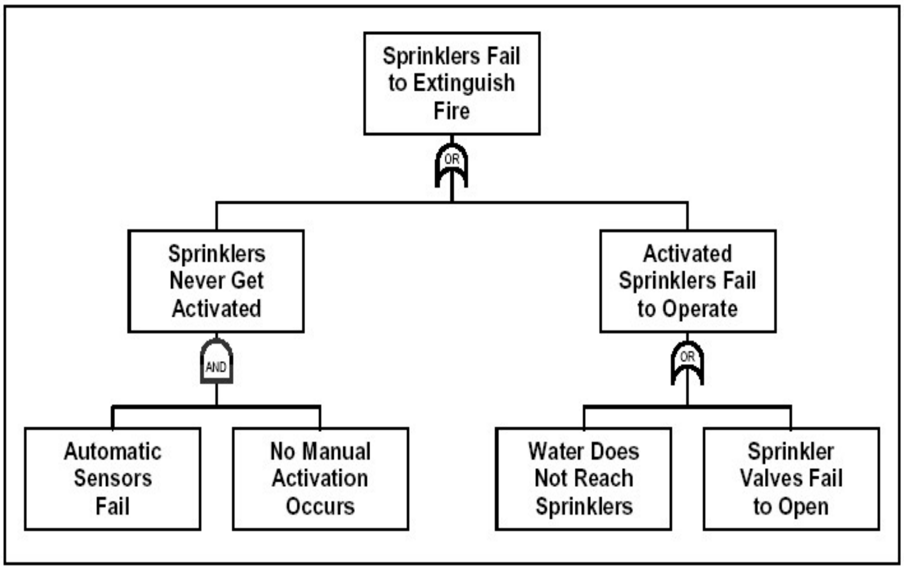


Figure 3: Example fault tree

- **Decision tree:** A decision tree is a method for representing the possible outcomes following a succession of events, combining points where the ensuing path is subject to choice and points where it is not [3]. The analysis operates similarly to an event or fault tree and the simplest decision trees consists of a set of initial choices and an event or fault tree associated with each.
- **Influence tree:** An influence diagram is a graphical representation of the relationship of the decisions and uncertainties in a decision problem [3]. The diagram is more flexible and less unidirectional than any type of tree diagram. It is designed to focus more on the elements of decision making and less on relevant underlying physical phenomena.

2.4.8 Event Tree as a Risk Analysis Method

A risk-based fire safety engineering method quantifies the safety level of a building. The method uses event tree technique and combines calculations of fire development with escape modelling for each scenario. The complete fire safety design process consists of the following five steps; qualitative design review, quantitative risk analysis, risk evaluation, sensitivity analysis and optimisation [30, 31, 32, 33]. The qualitative design review is used to highlight input related to fire safety in a systematic manner. The review collects all the necessary information for the forthcoming risk analysis. The risk is evaluated and the effectiveness of different fire safety strategies is assessed. A sensitivity analysis is performed to identify strong and weak aspects of the chosen fire safety design. Eventually there is a possibility to perform an optimisation where the adopted fire safety design is configured with the use of trade-offs to meet the acceptance criteria for the specific building. The process is illustrated in Figure 4.

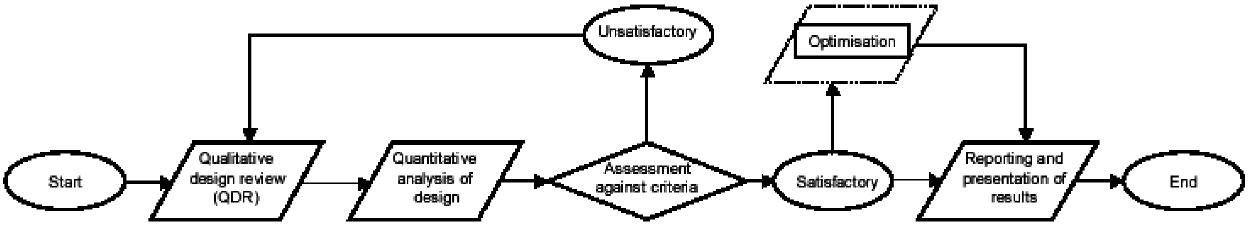


Figure 4: The basic fire safety design process

Fire is a transient process that affects a building and its occupants in different ways at different stages. The process of fire safety design is complicated by the fact that time is one of the key design parameters. When assessing the number of people exposed to untenable conditions a comparison between two time lines is made. One of these time lines represents the course of the fire, in terms of its size, rate of burning and smoke or toxic gas concentration. The other time line represents the response to the fire by the occupants. These time lines and the specific expressions used are presented in Figure 5.

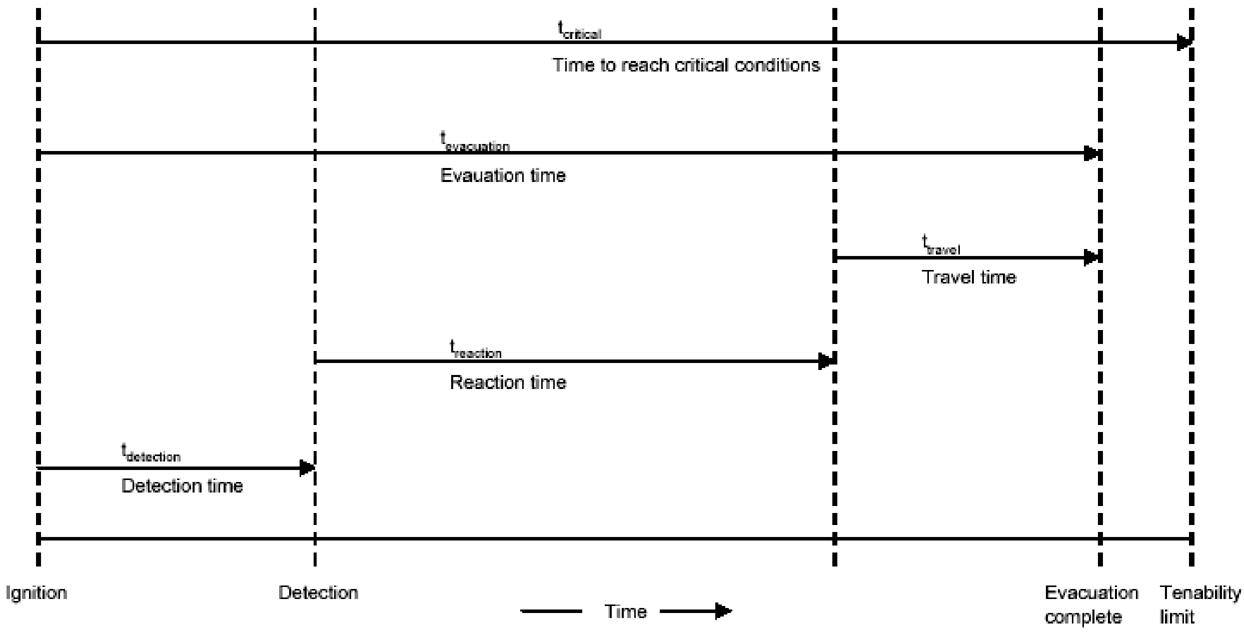


Figure 5: Example of a time line comparison of fire development and evacuation

The risk analysis itself is carried out by quantitatively evaluating a number of fire scenarios. The evaluation calculates the fire development and the evacuation process for all scenarios in the event tree. Event trees are logic diagrams, which can be used to illustrate the sequence of events involved in ignition, fire development and control, as well as the course of escape. Figure 6 shows an example of a simple event tree for a fire. The risk for each scenario is calculated by multiplying the probability of the specific scenario by its consequence. The total risk associated with a building is the sum of the risks for all scenarios in the event tree. Possible outcomes of such an event tree analysis are individual risk, average risk, degree of risk aversion and maximum consequence. The purpose with an event tree is to consider both successful and unsuccessful operation of the fire safety measures in the building.

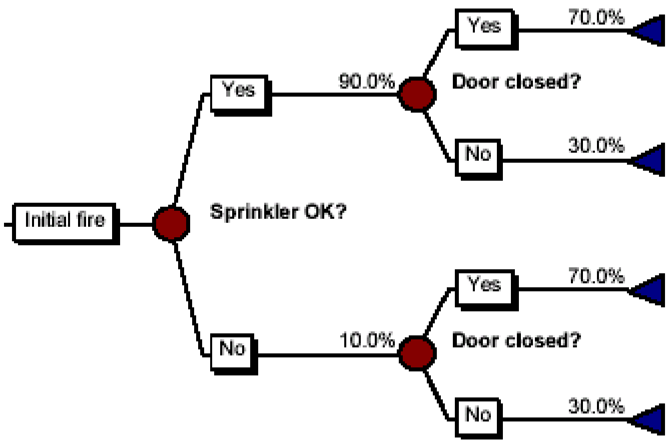


Figure 6: Example of part of a simple event tree.

To produce a definitive measure of the risk to life it would be necessary to consider every combination of fire source, fire scenario and target location within the building. However, the computational effort required increases with the number of sources, scenarios and targets considered. The fire development depends on fire growth, ceiling height, rate of heat release, ventilation, etc. Hazardous conditions are loss of visibility, exposure to toxic products and exposure to heat. The hazardous conditions are defined in the building regulations. The evacuation process is depending on detection, reaction and travel times.

The quantitative risk analysis makes it possible to evaluate some important risk measures. These are the individual risks and the societal risks. The individual risk measures consider the risk to an individual who may be at any point in the effect zones of incidents. The societal risk measures consider the risk to population that are in the effect zones of incidents. The individual risk is the probability that one or more people would be exposed to untenable conditions in case of fire. The societal risk could be expressed by an FN-curve or in this case the similar risk profile. The risk profiles for the analysed buildings are shown in Figure 7.

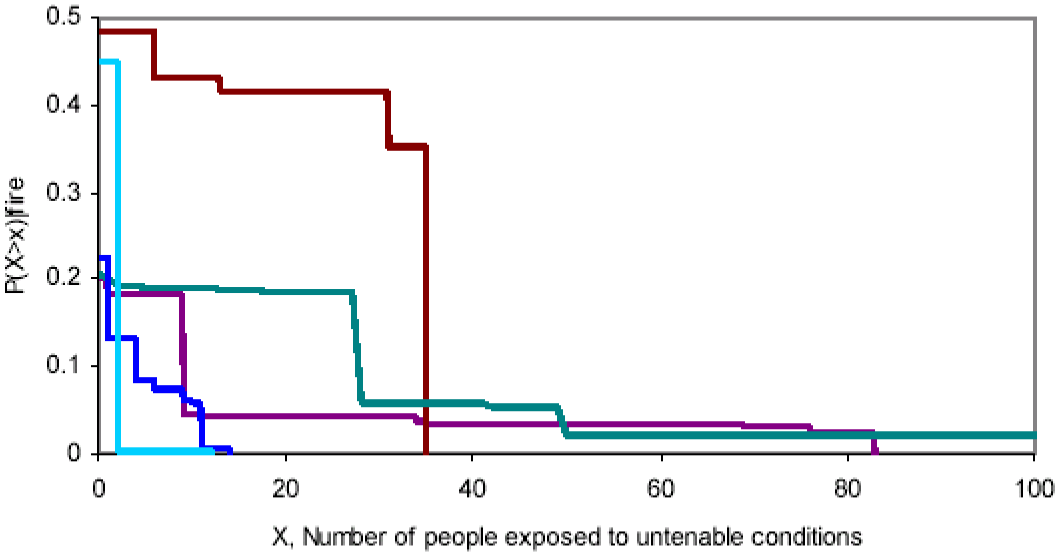


Figure 7: Risk profiles for all analysed buildings.

An detailed example of an event tree procedure for cultural heritage is given in annex D [34].

2.4.9 Fire Risk Assessment with Reliability Index β

Fire Risk analysis with the reliability index β is the most time consuming and complex way of evaluating the level of fire risk. The user of this system has to be familiar with different mathematical techniques as for example stochastic modelling and linear regression. The advantage is the precision of the results.

The risk-orientated analysis started with the selection of potential fire hazards, which could endanger safety systems or people inside the building. For these hazards it can be shown in a scenario event tree the various outcome for functioning/non-functioning fire alarms, sprinklers and emergency doors. The event tree indicates the routes by which the initial event can develop. At each branch, a question is posed related to the development of the event and branch probabilities are designed, based on statistical data. Each path through the event tree defines a scenario [25, 26].

For quantifying the hazard the safety can be described in terms for example for escape time. When a fire occurs in or in the vicinity of a room, only a certain time is available for human beings to remain in the room before it becomes untenable. Comparing the time available for escape with the time needed for it, the escape time margin can be calculated as [27]

$$G = t_a - t_e$$

With G = escape time margin
t_a = escape time available
t_e = escape time needed

This equation is referred to the state function. When the state function is equal to zero, implying that the escape time margin is zero, the state function is usually referred to the limit state function. In the present case the escape time available is determined by the interaction of the fire and the building. The energy release rate of the fire and the state of doors being open or closed are factors affecting the available time. The evacuation time is the sum of detection time, investigation time, behaviour and response time and movement time.

The times t_a and t_e, in turn are a function of basic variables that can either be constants or be subjects to uncertainty, i.e. random variables. The distributions of these random variables can be described by an expected value and a deviation from this expected value, i.e. by the mean and the standard deviation. Using random variables in the limit state function results are in a corresponding distribution of the escape margin.

The complete limit state function for the risk calculations here is

$$G = S\ ,\ U_s - D - t_{Inv} - R_{Fire} - R_{Neighb} - E - t_{Button}$$

S = time until untenable conditions develop as derived from a smoke transport model

U_s = model uncertainty of the smoke transport model

D = detection time (calculated or t_{Det})

t_{Inv} = investigation time for the staff

R_{Fire} = response time for the guest in the room in which there is fire

R_{Neighb} = response time for a guest in a neighbouring room

E = movement time ($t_{M\ Room}$, $t_{M\ Corr60}$, $t_{M\ Corr30}$)

t_{Button} = time for a guest to move to an alarm button

Not all the variables were used at the same time, some get the value of 0 for some sub scenarios. The variables S and calculated detection time are both functions of the fire growth rate α.

For the risk analysis method the life safety is expressed by the First Order Second Moment (FOSM) reliability index β. This measure represents a value for safety which is comparable between different solutions.

The correlation between the reliability index β and the individual risk measure can be approximated by the following relation

$P_{u,i} \cong 1 - \Phi(\beta)$

The safety index β provides a suitable measure of the safety. β has been used for a number of decades, mainly for the design of supporting structures and is quite simply a measure of risk. (β = 0, 1, 2 and 3 are roughly equivalent to risk levels of 50, 15, 2, and 0,1% probability of failure) [28,29].

The symbol Φ denotes the standardised normal distribution function and $p_{u,i}$ the probability of failure in sub scenario i due to the uncertainty of the variables. If the limit state function is linear and the basic variables are normally distributed, the expression becomes an equality. Other transformation functions than the normal can also be used in efforts to approximate the probability of failure. Also, the sum of the basic variables or functions of these can be approximated by a normal distribution in accordance with the central limit theorem.

Several methods are available to derive the FOSM reliability index β. For this the Rackwitz algorithm is employed. That method has been modified slightly in order to be able to consider non-normal distributions as well. For the reliability calculations the computer program STRUREL can be used.

The FOSM method that was likewise used provides sensitivity measures, showing how important the variables are with respect to each other and to the total reliability or safety. It should be recalled that importance factors can only be compared with each other within a specific scenario. There is only a weak link between different sub scenarios for a given importance factor allowing trends to be determined. This is due to the importance measures being scaled so that the square root of the sum of the importance measures equals one and their being obtained on the basis of information from one sub scenario at the time.

For the area of a nuclear power plant an example for the β index method is given in annex E.

2.4.10 Application of quantitative methods

The following table gives an overview on the different quantitative methods mentioned above and their ability to meet the acceptance criteria, reasons to disregard the method or positive features of the method.

method	meets the criteria	negative features	positive features
CRISP	yes	aimed at life safety	
FiRECAM	yes	for office buildings, specialists are needed for correct fire models	cost estimate, based on Canadian market
BFSEM	no: does not meet the “select protection” step		
FIEREAsystem	yes	use for light industrial buildings	
Petri net for Fire Safety Analysis	?	aimed at life safety, high workforce requirement	
ETA (Event Tree Analysis)	yes		life safety, damage area, cost benefit analysis included
Reliability Index ß	yes	complex and time consuming	

Table 3: Application of quantitative methods

3. Conclusion

In this report a review of literature about existing risk analysis methods are given. The different types of methods can be divided into

- Regulations and Checklists
- Ranking methods and
- Quantitative methods.

By **regulations** a satisfactory level of fire safety in a building will be achieved on a simple and safe way following the existing building codes. That has very little to do with risk assessment methods but give the easiest way of solving the fire safety problems. A number of detailed regulations have to be followed and therefore no “real” risk analysis is necessary.

Different types of **checklists** are often used as tools to make sure that a building fulfils the building code. Checklists can be the fastest way identifying risk features. But it is not possible to quantify the importance of such features. Another problem is, that a useful checklist has to be developed for a special type of building, therefore different lists must be established for different types of building. Both regulations and checklists are non-quantitative approaches.

Ranking methods or semi-quantitative methods are used in a wide range of applications. These methods have often been developed with the purpose of simplifying the risk assessment process for a specific type of building, process etc. Ranking methods remove most of the responsibility from the user to the producer of the method. A group of experts first has to identify every single factor that affects the level of safety or risk, which represents positive features (increase the level of safety) and negative features (decrease the level of safety). The importance of each factor has to be decided by assigning a value. This value is based on the knowledge and the experience of experts over a long time coming from insurance, fire brigade, fire consultants, scientists etc. Assigned values are then operated by some combination of arithmetic functions to achieve a single value. The value can be called as "risk index" and is a measure of the level of safety/risk in the object and it is possible to compare this to other similar objects and to a stipulated minimum value.

Methods aimed at property protection like SIA81, FRAME, FiRECAM and the insurance premium calculation systems have a semi quantitative background. This means that every ranking method which has a direct link with insurance premium rates has a built-in event tree analysis, but this is not discernible for the user.

An advantage of fire ranking methods is their simplicity, they are considered as very cost-effective tools. Another advantage of this method is the structured way in which the decision making is treated. This facilitates understanding of the system for persons not involved in the development process and makes it easier to implement new knowledge and technology into the system. Disadvantage of ranking methods is that they can only be used for a specific type of building or process etc.

Quantitative methods are the most informative approaches to fire risk assessment in that they produce quantitative values, typically produced by methods that can be traced back through explicit assumptions, data and mathematical relationships to the underlying risk distribution.

General for design based calculations engineering methodology is used to approach the design problem. Based on fire safety objectives, an engineering solution is derived. The purpose is then to demonstrate that the fire safety objectives are met. It is therefore natural for different types of buildings to adopt risk analysis methods and use them on fire engineering problems. An acceptable risk analysis method in the area of cultural heritage should be used also in other areas and should have shown its ability. Depending on the occurrence of one or more intermediate event different outcomes should be available.

Starting with a first event fire event sequences should be studied which could result in different consequences. All possible courses of accidents which can arise from specific events should be arranged in a convenient manner. The results of the model should provide a good framework for discussions also for non specialists. The influence of changes by single measures for the building should be seen on the result. If the principles of the method are known, everybody can understand why certain events do occur and why other combinations of events do not occur.

In many situations when fire safety must be evaluated there is no time or money available to perform a detailed quantitative risk analysis. Therefore there exists a need for simple semi-quantitative risk tools like risk index methods. This type of method has not been used so far in fire safety design since trade-off between different safety objectives in the building code has only been implicitly allowed so far. It is also unclear how to deal with aspects that are not covered in the building code, but affect fire safety in a building, e.g. some organisational and educational aspects.

In the context of fire safety design based on calculations, quantitative risk analysis is used to verify that threshold levels of risk are not exceeded for a design solution, i.e. the system subject to analysis. The method of verification is based on comparison of derived risk with some form of design criterion. The design criterion is determined by the risk analysis method used. The required method and the scope of the analysis depend on the complexity of the situation subject to analysis. It can vary from a simple quantitative analysis of the performance of a single component, e.g. the response time of a certain type of detector, to a complete qualitative risk analysis (QRA) including several scenarios, when uncertainties have to be taken into account explicitly. This can be done using the **event tree method**.

In the risk analysis procedure it is often necessary to examine a large number of scenarios with different chains of events. Each final event, outcome or scenario can be assigned a probability of occurrence. In order to structure the possible event sequences arising from an initial event, the event tree approach may be used. Event tree analysis can take into account human behaviour and the reliability of installed fire protection systems.

Using the event tree method has general advantages:

- It is easy to understand because of its binary system (yes/no) and its logical graphic surface with symbols,
- The event tree development procedure has seven steps:
    - Identification of initiating event,
    - Identification of safety function (both technical and human),
    - Construction of event tree,

    - Classify the outcomes,
    - Estimation of the conditional probability of each branch in the event tree,
    - Quantification of the outcomes,
    - Evaluation,
- An event tree often provides a very good framework for discussions. The point in the tree which is under discussion is clearly defined.
- Compatibility between different scenarios can be shown by the modular structure of an event tree,
- Event tree can be used for any questions like safety of people, damages, reliability, etc.
- The results are comprehensive F-N curves by which we obtain a graphic view of the consequences of the fire, versus the probability of occurrence,
- The total risk of a building is the sum of the risk for all scenarios in the event tree,
- Event trees are used to study or model event sequences which can result in different consequences.

Therefore the event tree methods is a strong tool to be used for QRA in the area of cultural heritages. The example in annex D showed the advantage of the event tree method and should be the basis preparing further examples for cultural heritages in the group. The example should be considered only as an example and the input data and results provided are not to be used in any other applications.

General there is a great uncertainty created when a limited number of scenarios are used in ETA. The numbers of scenarios are based on the selection of events to be included in the analysis. Events are chosen depending on the focus of the analysis. In a life safety analysis, events that are related to the fire development and to the possibility of successful escape are of more interest than events related to the fully developed fire and the integrity of fire compartments.

However, the uncertainty on scenario selection is not specific to the use of ETA. It does only become more “visible” in this transparent technique. All risk analyses methods model the risk and a model is always an attempt to describe and make prediction about real outcomes.

One of the most important things using ETA is which reliability data are available when modelling fire risks. There are numerous sources of information on the reliability of safety systems, the response by people, fire frequencies, fire development statistics, etc. But, how could an analyst be sure that the reference data available is suitable for the current analysis?

Solving fire risk problems with ETA techniques do require professional skills in fire modelling and risk analysis. If this skill is not available in the organisation, external assistance is appropriate.

Ranking methods do have the benefit that the analyst is not forced to provide as much data as when working with ETA. This does raise a few relevant questions: How could the analyst be sure that the selected ranking method is valid for specific analysis? To what extent is it possible to evaluate if the experts involved in the development of the ranking method was aware of the analyst specific situation? In an ETA, the analyst has full control of input and output, which is not the case when using many of the available ranking methods.

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Annex A:

The Evaluation of the Fire Safety Level in a Historic Centre in Lisbon

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Abstract

The big Chiado fire in 1988 occurred in the old part of Lisbon and involved 18 buildings, some of them from the 13th century. The buildings in this area have suffered changes along time as a response to new needs in the occupancy. After the fire, a systematic survey of about 200 buildings was done, for the identification of the building characteristics and buildings occupancy in that zone. The Swiss Gretener method for the evaluation of the fire risk was applied to 25 of those buildings. The results of that survey and of the risk analysis are summarised in the paper. The conclusions of a similar risk analysis applied to 116 buildings in another ancient quarter of Lisbon are also presented.

1. Introduction

After the Chiado fire, in downtown of Lisbon, in August of 1988, the Fire Brigades inspected 634 buildings close to the damaged zone. Most of the buildings, in this part of Lisbon, come from the reconstruction of the town after the big earthquake in 1755. The Swiss Gretener method [1] was applied to 25 buildings from this survey, in the boundary of the damaged zone (Fig. 1, zone 1) [2, 3], for the evaluation of the fire risk. In this area the streets are straight, large and perpendicular to each other. From another old part of Lisbon, having curve narrow streets and smaller buildings, a set of 31 representative buildings from the 116 studied was chosen (Fig. 1, zone 2) [4]. This study compares the fire risk analysis made in these two ancient parts of Lisbon.

2. The Swiss Gretener method

This fire risk analysis was based on the Swiss Gretener method, developed by the Swiss Insurance Association. This method establishes an admissible fire risk as a function of the use of the building, the level of the fire compartment and the number of persons inside it. The value of this admissible fire risk, Ru, must be greater than the existent fire risk, R.

$$R = AxB$$

The existent fire risk R is the product of the probability that a fire starts, A, and the fire hazard B (probable severity). The fire hazard B is a function of the potential hazard P, of the standard fire safety measures N, of the special fire safety measures S, and of the fire resistance of the building F.

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

The potential hazard P is influenced by the building contents, the quantity and kind of the materials and merchandises present, and by the size of the building itself. The fire safety measures N, S and F are a function of the water supply, the active fire preventive devices, the location, size and quality of fire brigades, the fire resistance of the structural elements, the size of the fire compartment and the kind of protection of the vertical communications.

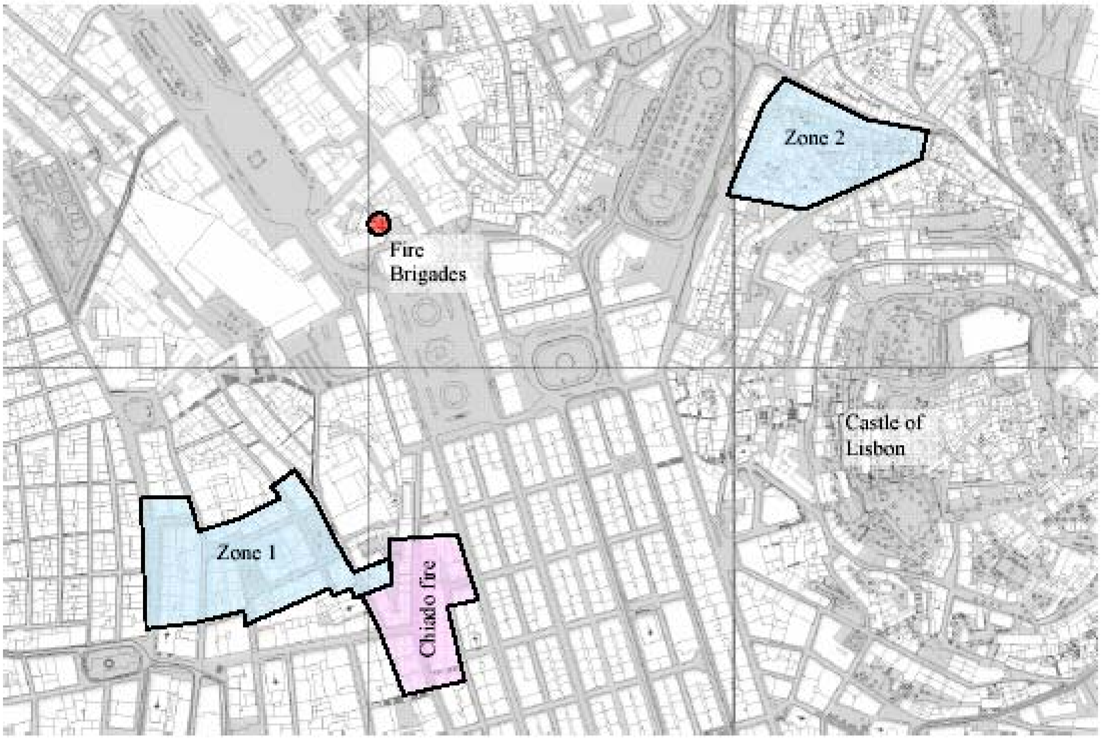

Fig 1 - Map of the old centre of Lisbon

3. Buildings Characteristics

3.1. Physical and geometric characteristics

The façades and gable walls of the buildings are made of stone masonry. Inside these walls there are wooden frameworks, as shown in figures 2 and 3. The wooden floors are supported by wood beams, which in turn are supported by the exterior walls and by wooden and stucco partition interior walls. Each flat opens directly to the vertical communications. Since all the studied buildings had no fire resistant partitions that could prevent fire from propagating to the whole building, they were classified as type V, according to the Gretener method, i.e., large volume buildings. The method was applied to two zones in the old part of Lisbon, zone 1, close to the Chiado fire zone, and zone 2, in the slope of the hill of the Castle of Lisbon (Fig. 1). The buildings and streets in zone 1 are larger than in zone 2. In zone 1 are located the best fashion stores, some banks, insurance companies and hotels.

Fig. 2 - Typical wooden frame of a 18th Century building

Fig. 3 - Inside view of a masonry wall with a wooden framework.

On the contrary, zone 2 is a very old typical residential area with traditional commerce. So, the mean floor area per building in zone 1 is about 400 m^2 while in zone 2, it is only 100 m^2 (Fig 4). The dimensions of the buildings in zone 2, having 20 m^2 of floor area in some extreme cases, contrast with

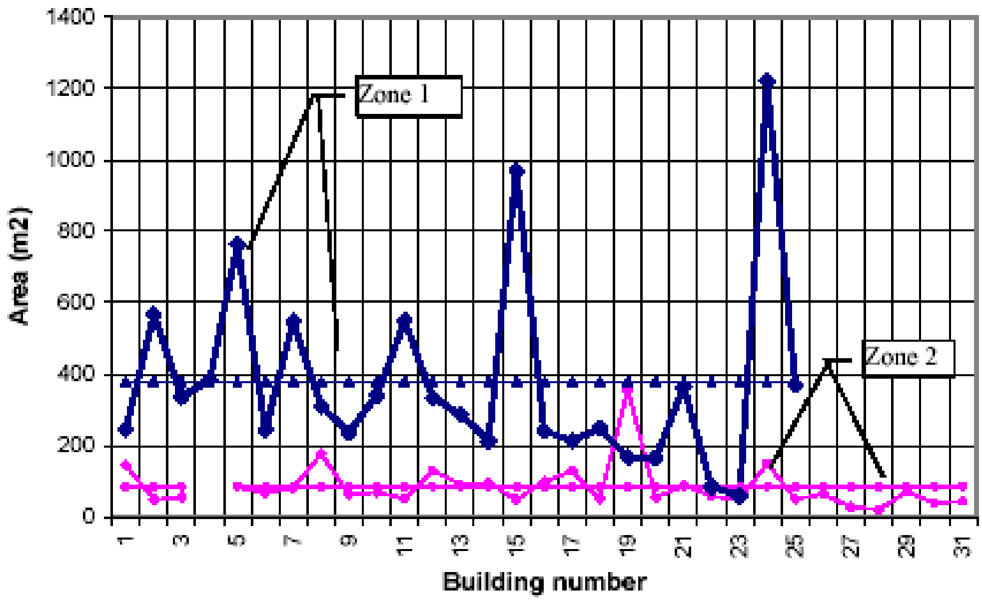

Fig 4 - Distribution of the floor area per building in zones 1 and 2

those of zone 1, where there is a building having a floor area higher than 1200 m^2. This leads to very different fire risk values. In some cases these large areas are due to illegal unprotected openings connecting several independent buildings.

3.2. Occupancy

The uses of the buildings were divided into three classes: apartments (hotel and residence), commerce (cloth and shoe shops, restaurants, supermarkets, shopping centres, etc.), and services (banks, insurance companies, engineering and architecture offices, trade offices, etc.). The distribution of the buildings of the two zones according to this classification is shown in Figs. 7 and 8. Figs. 5 and 6 show the type of occupancy per building in the two zones. Commercial activity represents about 30% in both zones. In zone 1 there has been during the last years an increase in the services, which lead to a corresponding decrease in the percentage of apartments occupancy. Illegal and unprotected connections between distinct buildings were detected in zone 1, justified by the users with the need of larger areas for services. In these cases both buildings were considered as a single one in the risk analysis. The decrease in the percentage of residential use, together with the fact that some of the oldest apartments are empty, has increased the fire risk after the labour hours.

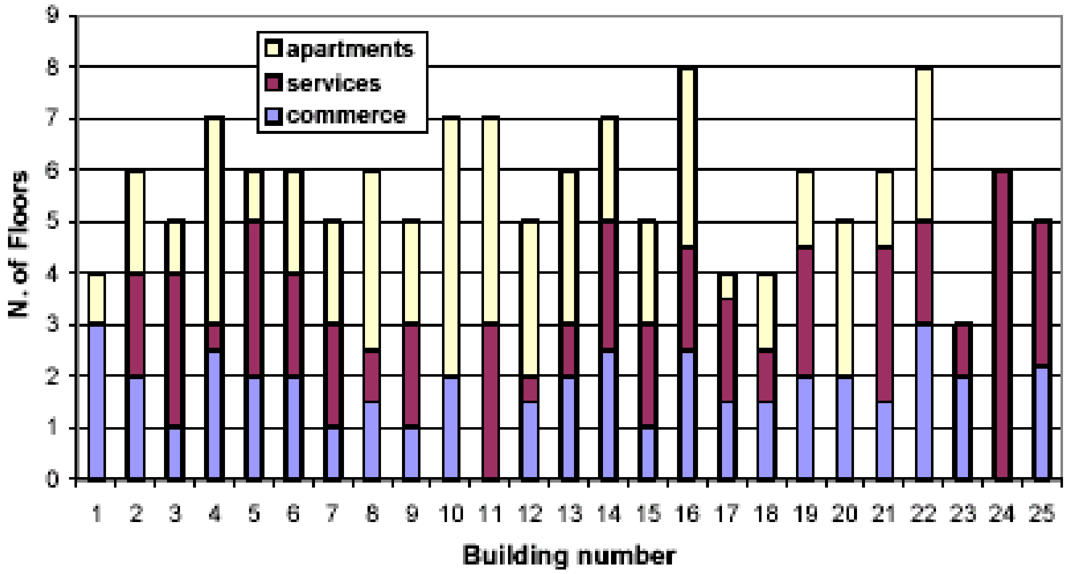

Fig. 5 - Occupancy per building in zone 1

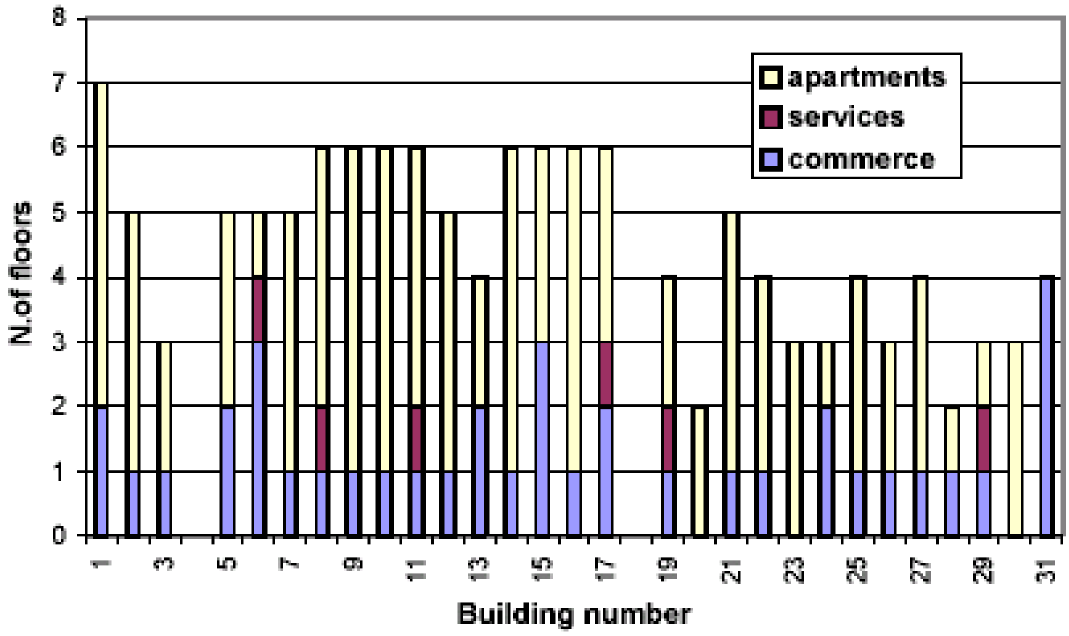

Fig. 6 - Occupancy per building in zone 2

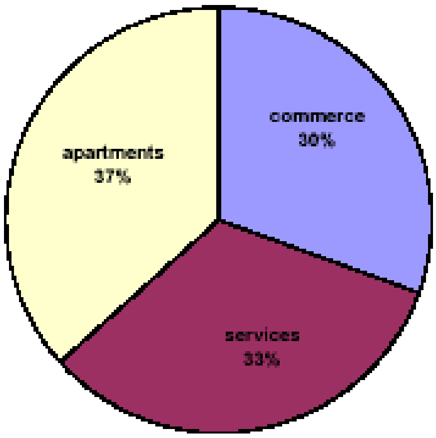

Fig. 7 - Occupancy distribution in zone 1

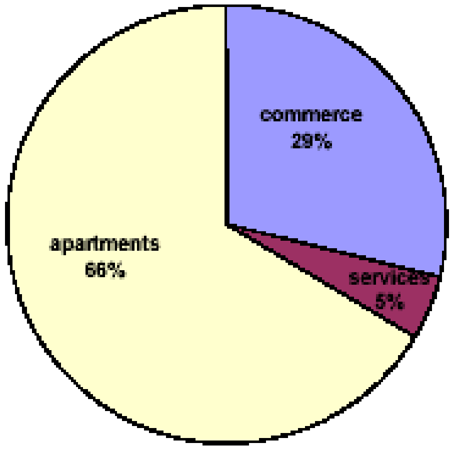

Fig. 8 - Occupancy distribution in zone 2

3.3. Fire safety measures

By the time this study was done no fire safety measures, such as portable fire extinguishers, automatic fire detectors, sprinklers, were found inside the commercial and services areas. There were no reels, hoses or water supply for the use of the firemen inside the buildings. Almost every building was equipped with fire hydrants in the façades. A water pressure of at least 2 bar and no restrictions in the water supply were considered in the analysis. No private fire brigades were considered. The location of at least one professional fire station is such that firemen can arrive to every point in these areas within less than 15 minutes. No mechanical or natural smoke and heat extraction was considered. The fire resistance of the interior walls and floors was neglected. The façades were considered to have a fire resistance of R60.

3.4 Evaluation of the fire risk

The use of the Gretener method is based on the assumption that the electrical and gas installations are in accordance with the last standards and well maintained. In many of the buildings in the centre of Lisbon these installations come from the beginning of the 20th century and the needs for these two kinds of energy are nowadays huge when compared to those years. The analysis was made independently of the bad condition of these installations. This very important aspect should therefore be kept in mind when analysing the results. The mean value of the fire risk in 31 buildings from zone 2 was 1.34 (Fig.9). The majority of the buildings had a fire risk above 1. From the few having a fire risk below 1, only the building nº 22 had a fire risk clearly small. The average fire risk of the whole 116 buildings from zone 2 was 1.48 and only a few of them had a fire risk under 1. This is mainly due to the small dimension of the floor area of these buildings and to their main use (residence). From the 116 buildings only 20 needed improvement in the fire safety measures.

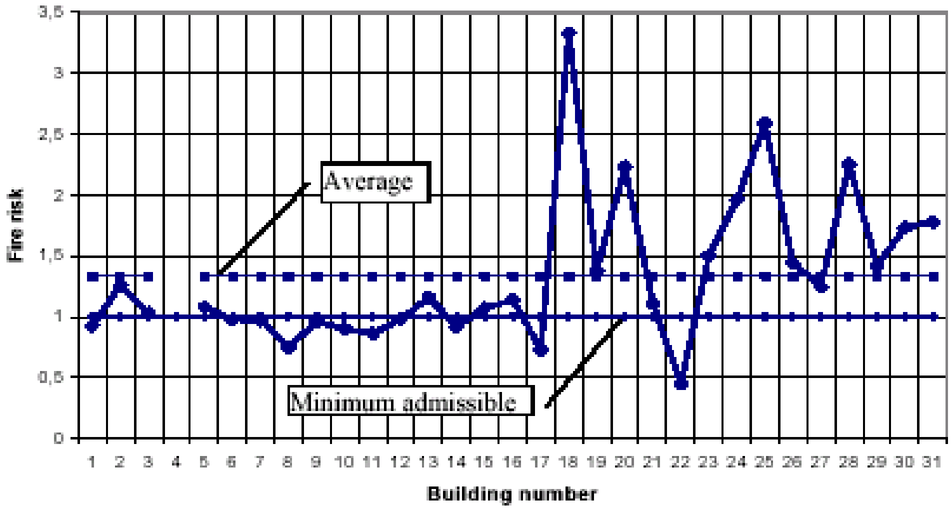

Fig. 9 - Fire risk evaluation in zone 2

The mean value of the fire risk of the buildings of zone 1 was 0.71, clearly below 1 (Fig. 10).

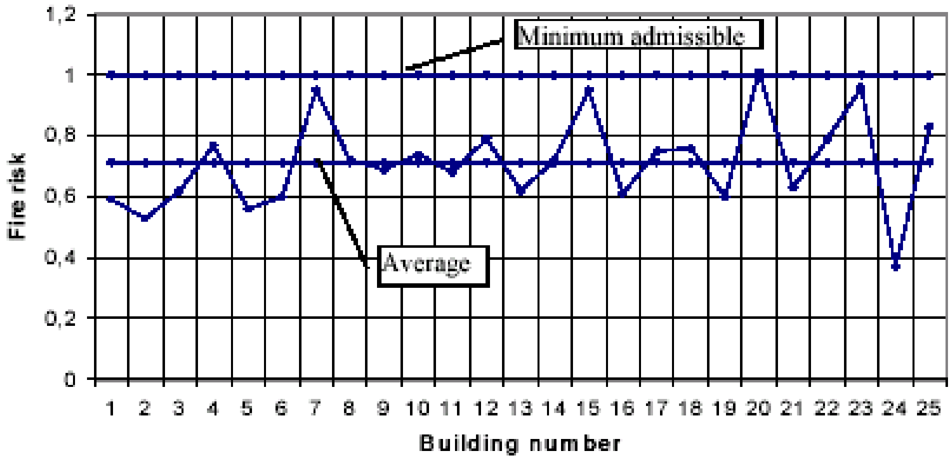

Fig. 10 - Fire risk evaluation in zone 1

Only one building had an acceptable fire risk. This low fire safety level is due to the greater dimensions of the buildings, together with their use as commercial stores and offices, and the absence of active fire safety systems. Without great interior or exterior architectural interventions, some fire safety measures could be undertaken, such as the installation of portable fire extinguishers, sprinkler systems, automatic detection systems and the training of the office and stores personnel for a first fire intervention. The recalculation of the fire risk after the introduction of these small changes brought the all the values above 1, with an average of 1.34 (Fig. 11).

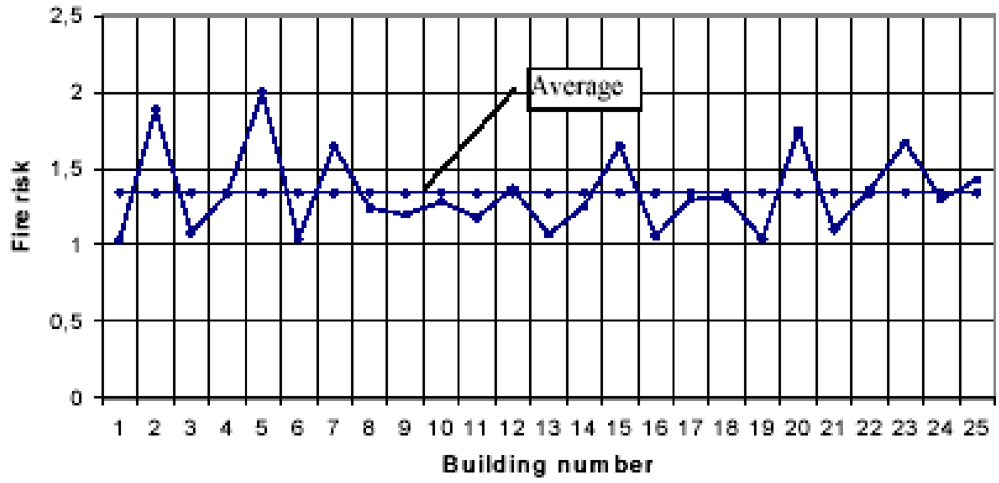

Fig. 11 - Fire risk evaluation in zone 1

4. Conclusions

The fire risk in two ancient zones of Lisbon was calculated using the Gretener method. One of the zones, a traditional and old residential area with small houses, showed a good fire safety per building, mainly due to the small fire load associated with the use of the buildings and to the small floor area per building. The other zone was mainly characterised by buildings with larger volumes used as commercial stores or offices, which in part had been subject to modifications, and having a lack in active and passive fire protection measures. Due to these characteristics the fire risk obtained was much bigger. The adoption of simple fire safety measures, such as the installation of portable fire extinguishers, sprinkler systems, automatic detection systems and the training of the office and stores personnel for a first fire intervention, was enough to bring the fire risk above the admissible value.

The Chiado fire was followed by a systematic verification of the state of all the electrical and power gas installations. Any change in the use of a building in an ancient urban zone must always be accompanied with the adoption of adequate fire protection measures.

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Annex B:

The Fire Assessment Method for Engineering (F.R.A.M.E)

Background

The severity of a risk is evaluated as “worst case consequence” without consideration for the effectiveness of the protection or for the duration of exposure. Such “worst case” becomes acceptable when the combination of exposure and low probability balance the severity of the case. A generally used mathematical expression for such an acceptable situation is the formula:

$$S * P * E \leq C$$

with P = measure of probability of occurrence

E = measure of exposure

C (constant) = measure of acceptable risk level

It should be noted that the severity, probability and exposure are linked to the same undesirable event.

The general formula can be written equally in logarithmic form as:

$\log (S * P * E) \leq \text{Log } C$

or $\log S + \log P + \log E \leq \text{Log } C$

or $\log (S * P) + \log E \leq \text{Log } C$

or $\log S + \log P \leq \text{Log } C - \log E$

or $\log (S * P) \leq \text{Log } C - \log E$

or also as: $\log (S *P) / (\text{Log } C - \log E) \leq 1$

which is similar to the formulas used in FRAME:

$$P/(D \times A) = P/D.\ (1.6 - \underline{f}(a, t, c, r, d) \leq 1$$

with P = Potential risk

D = Protection level

A = Acceptance level

P/D is the combined measure of severity and probability of occurrence and could be seen as the expression equal tot log (S * P), 1.6 = Log C and $\underline{f}$ (a, t, c, r, d) gives a measure of the exposure.

Severity models for fires

Most mathematical models express the severity of the thermal action of a fire as a function of the duration of the fire. The standard fire curves have a fast growing head, representing the start of flashover conditions and a more horizontal body, representative of a severe fire with a more or less constant rate-of-heat-release.

Natural fire models add to this curve a slow growing beginning, usually a t^2 - curve, representing the initial development of fire before flash-over, and a declining tail (linear or t^2) to represent the extinguishing phase of the fire.

The nearly horizontal part of the temperature-time curve of a natural fire during the fully developed phase covers two current scenarios in real fire conditions: it can be either a post-flash-over ventilation controlled fire or a situation where the heat output of the fire is nearly in balance with the heat absorption potential of the water flow applied by the fire brigade and sprinklers. In both cases a nearly constant RHR (rate-of heat-release) is assumed, and the duration of the fire is almost linear linked the available fire load.

The tail end of the fire extinguishing is not very interesting in risk assessment, as the key question is to define when and how often the thermal action will be sufficiently strong to cause the undesirable event. Introducing a beginning phase in a fire model is more significant, as it gives an indication of the time delay before the severe thermal action starts, and influences greatly the effectiveness of defensive such as fire operations and sprinkler actuation.

Additional parameters define the shape of natural fire curves. Generally, local conditions (ventilation, compartment size, etc.) are taken into account to transform the standard curve into a less or more severe fire model. the “equivalent time”-concept simplifies the fire severity evaluation to a comparison between the peak of a natural fire curve with the standard ISO 834 fire curve.

In FRAME the severity part of the fire model is distributed over several influence factors of the potential risk P. Basically, the fire load factor q is also a logarithmic expression of fire severity defined by the available fire load burning at a constant RHR, and fits perfectly the “log S”-part of the risk assessment.

$$q = 2/3 * \log (Q_i + Q_m) - 0.55$$

The 0.55 correction can be seen as that part of the fires’ heat output that is lost in the growing phase, goes into the smoke and is left in the extinguishing phase.

Localised versus fully developed fires

Generally speaking, localised fires are easier to handle: They do not impose a severe action on the building elements and can be approached for extinguishment. The transition from a localised fire to a fully developed fire is described in the scientific literature and expressed as a function of the fire heat release, the (square root) of the height between ceiling and floor, and the area of available ventilation openings.

In FRAME this relationship is found back in the ventilation factor v, which is calculated in a similar way with the log of the mobile fire load, the venting ratio k, and the (square root) of the height:

$$v = 0.84 + 0.1 \log Q_m – [k + (h)^{½}]^{½}$$

The effect of this factor in the potential risk P reflects an increased severity for high fire loads inside the compartment, and a decrease in severity when favourable ventilation conditions allow for localised fires. Whether the expression is a correct transcription of the scientific theories cannot be proven, but in practice properly engineered smoke venting systems always give a v-value slightly below 1, meaning that the fire severity is reduced, which is exactly what smoke venting systems do.

Rate-of-heat-release

Most fire models are very elementary when dealing with the heat release of fires. Yet, this aspect of fire development could be a key issue, especially for human safety, as the developing phase of the fire defines the time available for the escaping from the fire area. Scientific literature refers to a simple t^2-curve with a growth parameter value for slow, medium, fast and ultra-fast fire development.

In FRAME, three influence factors have been identified as contributing to the fire growth and hence to the fire severity:

- the volume/area ratio of the combustibles,
- the combustibility of the surfaces and
- the ignition characteristics of the surface materials.

These have been identified by three parameters and combined in the fire spread factor i.

$$i= 1 – (T/1000) – 0.1 * \log m + (M/10)$$

The combination and balancing of the three parameters is the result of reasoning and experienced guesswork.

The value of i will vary in the range of 0.5 to 1.65. The first value is representative for a storage of large blocks of concrete. The last one is typical for a heap of chips of expanded polystyrene. For most houses, the value of i will be about 1.2, assuming e.g. that m = 0.1, T = 200 and M = 3. Considering the logarithmic aspect of the basic formula, and the “household” fire (i = 1.2) as comparable to an ISO standard fire, the i-value of 0.5 means that a fire in a storage of concrete blocks should be comparable to 20 % of an ISO fire, the polystyrene fire (i = 1.65) could be 3 times as severe.

Severity evaluation

The three factors q, v and i combined, express the potential severity of the fire. The basic formula for q is logarithmic and complies with the “log S” aspect of the risk evaluation, and the i and v factors modify the fire load based severity factor q for ventilation and for RHR modifications. The other factors of P (potential risk) and the factors for D (protection degree) are related to the evaluation of probabilities and shall in fact transform the “log S” into a “log (S * E)”.

In FRAME, the combination of probability related factors is spread between P and D to fit practical design conditions, as some parameters are more linked to the buildings’ location, the others to the design of fire protection systems.

The probability of occurrence

What is really evaluated is not the probability of “a fire”, but the probability that the fire grows beyond control and reached the severity of the worst case. It is proposed using a single value for the probability, but in fire oriented developed methods using the event tree approach, the final “worst case” probability is split up in several sub-factors:

- one for the probability of ignition,
- one for the probability of early control,
- one for extinguishing by the fire brigade, sprinklers etc., and finally
- one for the probability that the uncontrolled fire engulfs the compartment and destroys it.

A similar combination of probability related factors is used in FRAME.

Probability of ignition

A number of fire safety studies consider the probability of ignition to be more or less uniform within compartments with similar occupancies, supported by statistical values. A few surveys have established such values for offices, housing, industrial building: they are in a range around 10^{-6} events per m² per year. The probability of ignition is therefore linked to the compartment floor area: the larger the compartment, the more likely a fire will occur. In prescriptive codes, compartment size limitations are apparently not linked to probability, but inspired by a concern for controllability of the fire by limiting the total quantity of combustibles (area x fire load).

The size of a compartment does not only define the number of (evenly) distributed ignition sources, but has also an impact on the time necessary to discover the fire, the occurrence of secondary ignition sources and the time necessary for the fire brigade to reach the seat of the fire.

In FRAME the ignition occurrence is completed with probability of early (human) detection of the fire. The shape of the compartment, the presence of intermediate galleries and multiple levels and the location versus the access level are also included. Building configuration is a risk aggravating element and is built in the area factor g, the level factor e, and the access factor z.

In the “natural fire concept” approach the increase in compartment size from 2500 m² to 10.000 m² causes a 15 % increase of fire severity value. For the same situation, the g-factor in FRAME doubles the value of P, which means a 100 % increase in fire severity value, reflecting not only the increased probability of ignition but also the decrease in controllability of the fire, resulting from the reduced capabilities of occupants and fire brigade to gain early control in a large building or less accessible spot.

It should be noted that in FRAME the g-factor does not intervene in the risk assessment for the occupants. As any developing fire is considered as “worst case for people”, the size of the compartment is not considered as relevant for severity and/or probability of the risk to persons. However, the size and shape of the compartment is considered in the calculation of A1 (Acceptance level for occupants), but this is a measure for the “exposure” and is dealt with separately.

Probability of control.

Statistical fire studies estimate the probability of early control by the occupants to be between 45 and 75 % of the cases, based on comparisons of the number of insurance claims and the number of fire brigade interventions in areas where both data were documented.

The probability of effective control by fire brigades and sprinklers again is derived from statistical information on insurance claims: e.g. from the ratio between medium value and high value insurance claims, an average fire brigade effectiveness (= limiting the fire to the room of origin) of 90 % is deduced. Sprinkler reliability is reasonably documented, so effective sprinkler control can be evaluated. The main causes of sprinkler system failure are also well known and the reliability of a particular sprinkler protection can be fairly well assessed. Anchor points are also the premium rebate percentages used by the insurance industry for active fire protection: higher rebates mean that the final cost of the fire is statistically lower and thus that corresponding fire protection systems are more reliable.

Reliability or probability of control in FRAME.

FRAME protection degree sub-factors W (water supply), N (normal protection), S (special protection), U (escape) and Y (salvage) deal with a large number of variants of design features, active fire protection devices and systems, fire fighting organisation, etc., as well with reliability aspects. Early control by the occupants is e.g. considered as part of the normal protection. It can be easily checked that the values used in the evaluation of these factors reflect the relative contribution of these features to the overall probability of successful control of fire before it reaches a critical situation. A lack of water supply on the premises results in a value for W, which just means that the fire brigade has one chance in two to extinguish the fire with the water in their trucks. The combined result is a “probability” correction for the risk assessment formula.

However, in FRAME the probability of control is written as a division by “reliability factors”. The values of N and W are in fact always $\leq$ 1, so 1/W and 1/N give “failure rates” $\geq$ 1: When the quality of the water supply and of the normal protection are substandard, the probability that a fire can be controlled is reduced. The values of N, S, F (and U and Y) are always $\geq$ 1: the higher these reliability factors, the lower the probability of failure.

Probability of collapse.

The probability of a final “victory” of fire depends in the end on the fire resistance of the structural and separating elements compared to the estimated duration of the fire. In general, codes require a certain level of fire resistance for structural and non-structural elements, compared with the available fire load as basis combined with a safety factor to reduce the probability of ruin by fire. A typical fire in a non-industrial environment has an average ISO 834 duration between 30 and 45 minutes.

Code requirements basically start with 30 minutes fire resistance for small and low-rise buildings, with increasing levels of requirements for medium height; taller and high rise buildings. As the fire duration does not basically change with the height of the building, the higher fire resisting requirements are in fact safety factor applications to reduce the probability of collapse in case the fire breaks out of the original fire compartment into other levels of the building. FRAME deals with this aspect in the resistance factor F and reckons with three assumptions.

The first is that the available stability in case of fire, is the joined result of the stability of structure the roof, floors, walls and internal separations, counting these in a 50 % , 25 %, 12.5 % and 12.5 % combination.

The second is that the value of F has to reflect the increased reliability of high fire resistance performance components, but also that the higher fire resistance may not be needed, certainly if the fire load is limited. It is dealt with in the first part of the F-formula, which gives a "bent" increase for F versus fire resistance. The absolute value of F also increases in the same way as the safety factors applied in building codes and at the same time follows broadly the same curve as the e-factor, so that the traditional link between building height and fire resistance requirements is also observed.

The third assumption is that building designers shall neither rely entirely on active fire protection systems or on passive fire resistance. this is accomplished by the second term of the F-formula, where the value of the special protection S is used to decrease the final value of F.

The importance of the exposure.

As fire exposure is a rather infrequent, the main consideration that reduces risk acceptability in fire situations will be the exposure time. The duration of the fire is only one element: the consequences of a fire are not ended when the fire is out, the business interruption or reduction can continue for several months, the reconstruction time for a building can be very long, and unique objects can be destroyed for ever.

These considerations have resulted in three slightly different formulas in FRAME to calculate the exposure, one for the property, one for the people, and one for the activities.

Exposure for people.

Usually people are considered to be safe, when they have left building on fire: the most evident measurement for the exposure is the evacuation time. But experience learns that the fire propagation in a building is not a uniform phenomenon and that rapid fire spread is the major for fire victims. This means that to evaluate correctly the exposure of people, evacuation time and fire propagation shall be jointly considered. In FRAME this results in the formula:

$$A1 = \{1.6 - a\} - (t + r)$$

with a = Activation factor

t = evacuation time factor

r = environment factor

The most significant factor for fire spread is the presence of ignitable surfaces, mostly building finishing and packaging materials. This is the reason why FRAME uses an r-factor, calculated with the immobile fire load Q_i (building materials) and the combustibility factor M (for the surface conditions).

The evacuation time shall be calculated for the actual conditions of the compartment and its occupants. The t-factor in FRAME does this, considering the whole path from the most remote corner of the compartment to the outside of the building, the capacity of the occupants to move and the compression effect when too much people use the same path. The formula is derived from scientific evidence on evacuation speed. A p-sub-factor increases the total evacuation time for unfavourable conditions, such as lack of awareness, reduced mobility and confusion.

One additional consideration that has been built in FRAME is the fact that multiple death accidents are considered to be far more unacceptable than single death situations. Some researchers in social behaviour claim that the risk acceptance is reduced by the square value of the number of possible deaths. Multiple deaths in a fire are likely to occur where long evacuation times come together with rapid fire spread. The combined values of high t- and r-factors will result in a value of $A < 1$, which means an increase in fire risk.

In such situations, protective action must be taken to counteract the exposure; the effect of such action is reflected by the value of U, the escape factor.

Exposure for property.

To measure the exposure for property, FRAME uses basically the monetary value of the property, transformed in the c2-factor. A similar approach exists in the insurance industry where an additionally premium is asked for high value properties. This practice is unusual for property values below 7 to 8 million Euro/US Dollar, which is also the lower limit used by FRAME. A correction is added to reflect the uniqueness of the content by the c1-factor.

An additional consideration made in FRAME is the fact that fire brigades will give priority to saving the occupants before starting large fire extinguishing operations. This means that lengthy evacuation will in fact increase the exposure for the property. The result is the formula:

$$A = \{1.6 - a\} - (t + c1 + c2)$$

Exposure for the activities.

An often-neglected aspect of fire risk is the business interruption potential. In fact, code requirements do not consider at all the impact of a fire on the economic life of a building. In the past, mostly insurance companies and corporate risk managers were concerned about it. Risk managers have spent a great deal of their efforts to bring business continuity after fire in the picture, and more recently authorities have become more concerned about the impact of fire on vital constructions such as major hospitals, power plants, ministries, road tunnels etc.

FRAME deals with this aspect of exposure in the following way. The duration of a fire is less important for its impact on the activities, as even a partial fire can stop an activity for several months, particularly if toxic combustion products like dioxins would be generated. Because of this "partial fire" consideration, the fire load factor 1 was not retained in the potential risk P2, as well as the correspondingly most effective protection (fire resistance) F for the protection degree D2.

The most evident elements for assessing the impact on a fire are also the monetary loss and the uniqueness of the content, so the c-factor is maintained. The evacuation time is not important for this issue.

In practice it appears that large losses in storage buildings do not have a big impact on business interruption, but that fires in controlling areas and bottleneck installations are very critical. A measure for this was found in the "added value/turnover" ratio, used as d-factor. It gives a good indication of the dependency of an activity on a certain location. The result of these considerations is the formula:

$$A2 = \{1.6 - a\} - (c1 + c2 + d)$$

An increased exposure for the activities can be compensated by a general improved fire protection, but also by specific local protection systems for bottleneck operations and by organisational measures to reduce dependency from one location, to relocate the business or to speed up restarts. These considerations are the basis for the specific formula for

$$D2 = N \times W \times S \times Y$$

with D2 = Protection level

N = Normal protection factor

W = Water supply factor

S = Special protection factor

Y = Salvage factor

Risk value expression.

The expression of the fire risk on a numerical scale is a convention. In the Gretener method a scale is used that locates the value of the risk in a range around 1. The most elementary reason is that Gretener originally wanted to develop a technical system for insurance premium rates, and these happen to be around 1 ‰ of the insured value. This risk value is also used in FRAME.

Definitions and Basic Formulas

1. Building and content:

The Fire Risk R is defined as the quotient of the Potential Risk P by the Acceptance Level A and Protection Level D

$$R = P / (A * D)$$

The Potential Risk P is defined as the product of the fire load factor q, the spread factor i, the area factor g, the level factor e, the venting factor v, and the access factor z.

$$P = q * i * g * e * v * z$$

The Acceptance Level A is defined as the maximum value 1.6 minus the activation factor a, the evacuation time factor t, and the value factor c.

$$A = 1.6 – a – t – c$$

The Protection Level D is defined as the product of the water supply factor W, the normal protection factor N, the special protection factor S and the fire resistance factor F.

$$D = W * N * S * F$$

2. Occupants:

The Fire Risk R1 is defined as the quotient of the Potential Risk P1 by the Acceptance Level A1 and the Protection Level D1

$$R1 = P1 / (A1 * D1)$$

The Potential Risk P1 is defined as the product of the fire load factor q, the spread factor i, the level factor e, the venting factor v, and the access factor z.

$$P1 = q * i * e * v * z$$

The Acceptance Level A1 is defined as the maximum value 1.6 minus the activation factor a, the evacuation time factor t, and the environment factor r.

$$A1 = 1.6 – a – t – r$$

The Protection Level D1 is defined as the product of the normal protection factor N and the escape factor U.

$$D1 = N * U$$

3. Activities

The Fire Risk R2 is defined as the quotient of the Potential Risk P2 by the Acceptance Level A2 and the Protection Level D2.

$$R2 = P2 / (A2 * D2)$$

The Potential Risk P2 is defined as the product of the spread factor i, the area factor g, the level factor e, the venting factor v, and the access factor z.

$$P2 = i * g * e * v * z$$

The Acceptance Level A2 is defined as the maximum value 1.6 minus the activation factor a, the value factor c, the dependency factor d.

$$A2 = 1.6 – a – c – d$$

The Protection Level D2 is defined as the product of the water supply factor W, the normal protection factor N, the special protection factor S and the salvage factor Y.

$$D2 = W * N * S * Y$$

These formulas show the similarity between the three parts of each calculation.

Calculating the Potential Risks

The Potential Risks P, P1 and P2 are defined as products of the fire load factor q, the spread factor i, the area factor g, the level factor e, the venting factor v, and the access factor z.

The fire load factor q indicates how much can burn per area unit (m²). In practice, FRAME provides t tables with reasonable estimates of the values of Q_i (fire load immobile) and Q_m (fire load mobile) based on building construction types and occupancy classification.

$$q = 2/3 * \log (Q_i + Q_m) – 0.55$$

The fire spread factor i indicates how easy a fire can spread through a building. It is calculated from the average dimension of the content m, the flame propagation class M, and the destruction temperature T. FRAME gives guidelines how to define these parameters.

$$i = 1 - \frac{T}{1000} - 0.1 * \log m + \frac{M}{10}$$

The area factor g indicates the horizontal influence of the fire. The factor g is calculated with the values of 1, the theoretical length of the compartment, and of b, the equivalent width, expressed in meter. The length “l” of a compartment is the longest distance between the centres of two sides of the compartments’ perimeter. The equivalent width “b” is the quotient of the total area of the compartment by the theoretical length.

$$g = \frac{b + 5 * \sqrt[3]{l * b^2}}{200}$$

The level factor e indicates the vertical influence of the fire and will be calculated from the level number E. The main access level has number E = 0. Levels above the access are numbered 1, 2, 3, etc. Levels below the access level are numbered –1, -2, -3, etc.

$$e = \Phi(|E|)$$

The venting factor v indicates the influence of smoke and heat inside the building. It compares the venting capacity of the compartment with the sources of smoke.

$$v = 0.84 + 0.1 * \log Qm - \sqrt{k * \sqrt{h}}$$

The access factor z indicates for outside help to get into the fire area.

$$Z = \Phi(b, Z, H^+, H^-)$$

Calculating the Acceptance Levels

The acceptance level reflects the fact that the people can live with the threat of fire up to a certain level, as long as fire is an unlikely event, and as long as the consequences are not too irreversible. The acceptance levels are calculated with the activation factor a, the evacuation time factor t, the environment factor r and the dependency factor d.

The way to define the activation factor a is to go through a review of possible fire sources, and to sum all relevant values, referring to the following types of fire sources: Main activities, secondary activities, process and room heating systems, electrical installations, presence of flammable gases, liquids and dusts.

$$a = \Sigma a_i$$

The evacuation time factor t is calculated with the dimensions of the compartment, the number of people, exit units and exit paths, and the mobility factor.

$$t = \frac{p * x * [(b+l) + (X/x) + 1.25 * H^{+} + 2 * H^{-}] * (b+l)}{800 \quad * \quad K * [1.4 * x * (b+l) - 0.44 * X]}$$

Content factor c will evaluate the possibility to replace the building and its content, and the monetary value. Environment factor r will reflect the running speed of fire, and the dependency factor d will measure how much a business can be touched by fire.

Calculating the Protection Levels

The protection levels are calculated with W, the water supply factor; N, the normal protection factor; S, the special protection factor; F, the fire resistance factor; U, the escape factor and Y, the salvage factor.

Water supply factor W considers the type and capacity of water storage and distribution network.

$$W = 0.95^{w}$$

Normal protection factor N considers guard services, manual fire fighting, time delay of fire brigade intervention, personnel training.

$$N = 0.95^{n}$$

Special Protection factor S considers automatic detection, reliability of water supplies, automatic protection, and fire brigade force.

$$S = 1.05^{s}$$

Fire resistance factor F considers of the structural elements, outside walls, ceiling or roof and inner walls. Escape factor U considers every measure that speeds up the evacuation or slows down the early development of fire.

$$U = 1.05^{u}$$

Salvage factor Y considers protection of critical items, and contingency planning.

$$Y = 1.05^{Y}$$

EXAMPLE: Historic Building: 13-15th century monastery used as Museum and Cultural Centre.

The manager of this building wanted to know is the level of safety comparable to what exists in a more recent building.

Construction: 2250 m² in a U-shape, 3 levels, very thick stone and masonry walls, wooden floors, some with tiles, slate roof on massive oak structure. No effective compartmentation because of 2 monumental stairs joining the 3 levels.

The building is accessible on one side only, the other sides are adjacent buildings and a river; the city water supply is only a 3" pipe. The building is equipped with extinguishers, hose reels, a fire alarm system and partial fire detection. Notification to the fire brigade is by the staff.

The fire load is low, except for a library with old books, located in the North wing. This library has a wooden floor and a decorated wooden ceiling, which is also the floor of meeting room at the upper level. This room can receive about 150 persons and has one adequate and one limited exit to stairs. In the central wing, there is a small restaurant and a kitchen.

Maximum occupancy is 500 persons for meetings or conferences. The building has several exits, but some exit doors turn to the inside.

FRAME-Calculations

Actual situation: R = 1.34; R1 = 3.80; R2 = 0.90

Conclusion: A limited damage can be expected, but the safety of such a large number of persons (500) is not guaranteed.

1st proposition for improvement: Provide a vertical compartmentation in 3 sections, by installing fire doors in the existing walls; extend the automatic detection to the whole building.

Result for the central wing: R = 0.46; R1 = 0.93; R2 = 0.43

this is acceptable

Result for the library and meeting room: R = 0.50; R1 = 1.71; R2 = 0.31

this is insufficient: a fire in the library can hamper the evacuation of the meeting room.

Additional proposals: Provide a local sprinkler system for the library

A new calculation gives: R = 0.25; R1 = 0.90; R2 = 0.17 for the library,

this is a good level of safety.

As a temporary measure: The number of people in the meeting room can be limited to the capacity of the smaller stair (less than 100).

This gives: R = 0.35; R1 = 1.03; R2 = 0.30 for the conference room,

this is also an adequate level of safety.

Annex C:

The Fire Risk Index Method (Version 1.2)

This is Version 1.2 of the Risk Index method for multistory apartment buildings. The list below presents different decision levels; Objectives, Strategies and Parameters. The parameter grades are calculated by using the grading schemes presented in this paper. In the grading schemes the two lowest decision levels are used; Sub-Parameters and Survey Items. Currently, we shall only consider ordinary occupancies.

Policy:
Provide acceptable fire safety level in multi-story apartment buildings
Def: Multi-story apartment buildings shall be designed in a way that ensures sufficient life safety and property protection in accordance with the objectives listed below.

Objectives:

O_1 Provide life safety

Def: Life safety of occupants in the compartment of origin, the rest of the building, outside and in adjacent buildings and life safety of fire fighters

O_2 Provide property protection

Def: Protection of property in the compartment of origin, in the rest of the building, outside and in adjacent buildings

Strategies:

S_1 Control fire growth by active means

Def: Controlling the fire growth by using active systems (suppression systems and smoke control systems) and the fire service.

S_2 Confine fire by construction

Def: Provide structural stability, control the movement of fire through containment and use fire safe materials (linings and facade material). This has to do with passive systems or materials that are constantly in place.

S_3 Establish safe egress

Def: Cause movement of occupants and provide movement means for occupants. This is done by designing detection systems, signal systems, by designing escape routes and by educating or training the occupants. In some cases the design of the escape route may involve action by the fire brigade (escape by ladder through window).

S_4 Establish safe rescue

Def: Protect the lives and ensure safety of fire brigades personnel during rescue. This is done by providing structural stability and preventing rapid unexpected fire spread and collapse of building parts

Parameters:

P_1 Linings in apartment
Def: Possibility of internal linings in an apartment to delay the ignition of the structure and to reduce fire growth

P_2 Suppression system
Def: Equipment and systems for suppression of fires

P_3 Fire service
Def: Possibility of fire services to save lives and to prevent further fire spread

P_4 Compartmentation
Def: Extent to which building space is divided into fire compartments

P_5 Structure - separating
Def: Fire resistance of building assemblies separating fire compartments

P_6 Doors
Def: Fire and smoke separating function of doors between fire compartments

P_7 Windows
Def: Windows and protection of windows, i.e. factors affecting the possibility of fire spread through the openings

P_8 Facade
Def: Facade material and factors affecting the possibility of fire spread along the facade

P_9 Attic
Def: Prevention of fire spread to and in attic

P_{10} Adjacent buildings
Def: Minimum separation distance from other buildings

P_{11} Smoke control system
Def: Equipment and systems for limiting spread of toxic fire products

P_{12} Detection system
Def: Equipment and systems for detecting fires

P_{13} Signal system
Def: Equipment and systems for transmitting an alarm of fire

P_{14} Escape routes
Def: Adequacy and reliability of escape routes

P_{15} Structure - load-bearing
Def: Structural stability of the building when exposed to a fire

P_{16} Maintenance and information
Def: Inspection and maintenance of fire safety equipment, escape routes etc. and information to occupants in suppression and evacuation

P_{17} Ventilation system
Def: Extent to which the spread of smoke through the ventilation system is prevented.

Grading schemes

P_1. LININGS IN APARTMENT

DEFINITION: Possibility of internal linings in an apartment to delay the ignition of the structure and to reduce fire growth

PARAMETER GRADE:
This refers to the worst lining class (wall or ceiling) that is to be found in an apartment.

LINING CLASS						GRADE
Suggestions to Euroclasses	**Typical products**	**DK**	**FIN**	**NO**	**SWE**	
A1	Stone, concrete	A	1/I	In1	I	**5**
A2	Gypsum boards	A	1/I	In1	I	**5**
B	Best FR woods (impregnated)	A	1/I	In1	I	**4**
C	Textile wall cover on gypsum board		1/II 2/-	In2	II	**3**
D	Wood (untreated)	B	1/-	In2	III	**2**
E	Low density wood fiberboard	U	U	U	U	**1**
F	Some plastics	U	U	U	U	**0**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_2. SUPPRESSION SYSTEM

DEFINITION: Equipment and systems for suppression of fires

SUB-PARAMETERS:

Automatic sprinkler system

Type of sprinkler (N = no sprinkler, R = residential sprinkler, O = ordinary sprinkler) and Location of sprinkler (A = in apartment, E = in escape route, B = both in apartment and escape route)

SURVEY ITEMS	**DECISION RULES**						
Type of sprinkler	N	R	R	R	O	O	O
Location of sprinkler	-	A	E	B	A	E	B
GRADE	N	M	L	H	M	L	H

(N = no grade, L = low grade, M = medium grade and H = high grade)

Portable equipment

N	None
F	Extinguishing equipment on every floor
A	Extinguishing equipment in every apartment

PARAMETER GRADE:

SUB-PARAMETERS	DECISION RULES											
Automatic sprinkler system	N	N	N	L	L	L	M	M	M	H	H	H
Portable equipment	N	F	A	N	F	A	N	F	A	N	F	A
GRADE	**0**	**0**	**1**	**1**	**1**	**2**	**4**	**4**	**4**	**5**	**5**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_3. FIRE SERVICE

DEFINITION: Possibility of fire services to save lives and to prevent further fire spread

SUB-PARAMETERS:

Capability of responding fire service (P_{3a})

CAPABILITY OF RESPONDING FIRE SERVICE	GRADE
No brigade available	0
Fire fighting capability only outside the building	1
Fire fighting capability but no smoke diving capability	2
Fire fighting and smoke diving capability	4
Simultaneous fire fighting, smoke diving and external rescue by ladders	5

(Minimum grade = 0 and maximum grade = 5)

Response time of fire service to the site **(P_{3b})**

RESPONSE TIME (min)	GRADE
> 20	0
15 – 20	1
10 – 15	2
5 – 10	3
0 – 5	5

(Minimum grade = 0 and maximum grade = 5)

Accessibility and equipment (i.e. number of windows (or balconies) that are accessible by the fire service ladder trucks) **(P_{3c})**

ACCESSIBILITY AND EQUIPMENT	GRADE
Less than one window in each apartment accessible by fire service ladders	0
At least one window in each apartment accessible by fire service ladders	3
All windows accessible by fire service ladder	5

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_3 is:

(0.31 × Capability + 0.47 × Response time+ 0.22 × Accessibility and equipment) =

Resulting grade:

P_4. COMPARTMENTATION

DEFINITION: Extent to which building space is divided into fire compartments

PARAMETER GRADE:

MAXIMUM AREA IN FIRE COMPARTMENT	GRADE
> 400 m^2	0
200 - 400 m^2	1
100 – 200 m^2	2
50 – 100 m^2	3
< 50 m^2	5

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_5. STRUCTURE - SEPARATING

DEFINITION: Fire resistance of building assemblies separating fire compartments

SUB-PARAMETERS:

Integrity and insulation (P_{5a})

INTEGRITY AND INSULATION (EI)	GRADE
EI < EI 15	0
EI 15 ≤ EI < EI 30	1
EI 30 ≤ EI < EI 45	3
EI 45 ≤ EI < EI 60	4
EI 60 ≥ EI	5

(Minimum grade = 0 and maximum grade = 5)

Firestops at joints, intersections and concealed spaces (P_{5b})

STRUCTURE AND FIRESTOP DESIGN	GRADE
Timber-frame structure with voids and no fire stops	0
Ordinary design of joints, intersections and concealed spaces, without special consideration for fire safety.	1
Joints, intersections and concealed spaces have been tested and shown to have endurance in accordance with the EI of other parts of the construction.	2
Joints, intersections and concealed spaces are specially designed for preventing fire spread and deemed by engineers to have adequate performance.	3
Homogenous construction with no voids	5

(Minimum grade = 0 and maximum grade = 5)

Penetrations (P_{5c})
Penetrations between separating fire compartments

PENETRATIONS	GRADE
Penetrations with no seals between fire compartments	0
Non-certified sealing systems between fire compartments	1
Certified sealing systems between fire compartments	2
Special installation shafts or ducts in an own fire compartment with certified sealing systems to other fire compartments	3
No penetrations between fire compartments	5

(Minimum grade = 0 and maximum grade = 5)

Note: If P5c = 0, then P5a, b and d must = 0.

Combustibility (P_{5d})

Combustible part of the separating construction

COMBUSTIBLE PART	GRADE
Both separating structure and insulation are combustible	0
Only the insulation is combustible	2
Only the separating structure is combustible	3
Both separating structure and insulation are non- combustible	5

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_5 is:

(0.35 × Integrity and insulation + 0.28 × Fire stops at joints, Intersection and concealed spaces + 0.24 × Penetrations + 0.13 × Combustibility) =

Note: If grade for penetrations = 0, then the parameter grade = 0

Resulting grade:

P_6. DOORS

DEFINITION: Fire separating function of doors between fire compartments

SUB-PARAMETERS:

Doors leading to escape route (P_{6a})

Integrity and insulation (= EI)

(A = EI < EI 15, B = EI 15 ≤ EI < EI 30, C = EI 30 ≤ EI < EI 60, D = EI ≥ EI 60)

and Type of closing (M = manually, S = self-closing)

SURVEY ITEMS	DECISION RULES							
Integrity and insulation	A	A	B	B	C	C	D	D
Type of closing	M	S	M	S	M	S	M	S
GRADE	0	1	1	3	2	4	3	5

(Minimum grade = 0 and maximum grade = 5)

Doors in escape route (P_{6b})

Integrity and insulation (= EI)

(A = EI < EI 15, B = EI 15 ≤ EI < EI 30, C = EI 30 ≤ EI < EI 60, D = EI ≥ EI 60)

and Type of closing (M = manually, S = self-closing)

If no doors are needed in the escape routes the highest grade is received.

SURVEY ITEMS	DECISION RULES								
Integrity and insulation	A	A	B	B	C	C	D	D	-
Type of closing	M	S	M	S	M	S	M	S	-
GRADE	0	1	1	3	2	4	3	5	5

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_6 is:
(0.67 x Doors leading to escape route + 0.33 x Doors in escape route) =

Resulting grade:

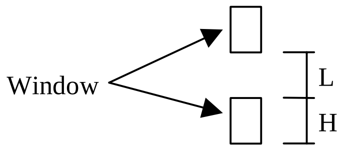
P_7. WINDOWS

DEFINITION: Windows (and other facade openings) and protection of these, i.e. factors affecting the possibility of fire spread through the openings

SUB-PARAMETERS:

Relative vertical distance

This is defined as the height of the window divided by the vertical distance between windows



Relative vertical distance, R = L/H

(A = R < 1, B = R ≥ 1)

Class of window

(C = window class < E 15, D = window class ≥ E 15, E = tested special design solution or window class ≥ E 30)

PARAMETER GRADE:

SUB-PARAMETERS	**DECISION RULES**					
Relative vertical distance	A	A	A	B	B	B
Class of window	C	D	E	C	D	E
GRADE	**0**	**3**	**5**	**2**	**5**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_8. FACADES

DEFINITION: Facade material and factors affecting the possibility of fire spread along the facade

SUB-PARAMETERS:

Combustible part of façade (P_{8a})

COMBUSTIBLE PART	GRADE
> 40 %	0
20 – 40 %	2
< 20 %	3
0 %	5

(Minimum grade = 0 and maximum grade = 5)

Combustible material above windows (P_{8b})

COMBUSTIBLE MATERIAL ABOVE WINDOWS?	GRADE
Yes	0
No	5

(Minimum grade = 0 and maximum grade = 5)

Void (P_{8c})

Does there exist a continuous void between the facade material and the supporting wall?

TYPE OF VOID	GRADE
Continuous void in combustible facade	0
Void with special design solution for preventing fire spread	3
No void	5

PARAMETER GRADE:

The Calculation and Result for P_8 is:

(0.41 x Combustible part of façade + 0.30 x Combustible material above windows + 0.29 x Void) =

Resulting grade:

P_9. ATTIC

DEFINITION: Prevention of fire spread to and in attic

SUB-PARAMETERS:

Prevention of fire spread to attic (e.g. is the design such that ventilation of the attic is not provided at the eave? The most common mode of exterior fire spread to the attic is through the eave. Special ventilation solutions avoid this.)

N	No
Y	Yes

Fire separation in attic (i.e. extent to which the attic area is separated into fire compartments)

MAXIMUM AREA OF FIRE COMPARTMENT IN ATTIC	GRADE
No attic	H
< 100 m^2	M
100 – 300 m^2	L
300 – 600 m^2	L
> 600 m^2	N

(N = no grade, L = low grade, M = medium grade and H = high grade)

PARAMETER GRADE:

SUB-PARAMETERS	DECISION RULES							
Prevention of fire spread to attic	N	N	N	N	Y	Y	Y	Y
Fire separation in attic	N	L	M	H	N	L	M	H
GRADE	**0**	**1**	**2**	**5**	**2**	**3**	**4**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_{10}. ADJACENT BUILDINGS

DEFINITION: Minimum separation distance from other buildings. If the buildings are separated by a firewall this is deemed to be equivalent to 8 m distance.

PARAMETER GRADE:

DISTANCE TO ADJACENT BUILDING, D	GRADE
D < 6 m	**0**
6 ≤ D < 8 m	**1**
8 ≤ D < 12 m	**2**
12 ≤ D < 20 m	**3**
D ≥ 20 m	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_{11}. SMOKE CONTROL SYSTEM

DEFINITION: Equipment and systems in escape routes for limiting spread of toxic fire products

SUB-PARAMETERS:

Activation of smoke control system

N	**No smoke control system**
M	Manually
A	Automatically

Type of smoke control system

N	Natural ventilation through openings near ceiling
M	Mechanical ventilation
PN	Pressurisation and natural ventilation for exiting smoke
PM	Pressurisation and mechanical ventilation for exiting smoke

PARAMETER GRADE:

SUB-PARAMETERS	DECISION RULES								
Activation of smoke control system	N	M	M	M	M	A	A	A	A
Smoke vent openings	-	N	M	PN	PM	N	M	PN	PM
GRADE	**0**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_{12}. DETECTION SYSTEM

DEFINITION: Equipment and systems for detecting fires

SUB-PARAMETERS:

Amount of detectors
Detectors in apartment (N = none, A = at least one in every apartment, R = more than one in every apartment) and Detectors in escape route (N = no, Y = yes)

SURVEY ITEMS	DECISION RULES					
Detectors in apartment	N	N	A	R	A	R
Detectors in escape route	N	Y	N	N	Y	Y
GRADE	N	L	L	M	H	H

(N = no grade, L = low grade, M = medium grade and H = high grade)

Reliability of detectors

Detector type (H = heat detectors, S = smoke detectors) and Detector power supply (B = battery, P = power grid, BP = power grid and battery backup)

SURVEY ITEMS	DECISION RULES					
Detector type	H	H	H	S	S	S
Detector power supply	B	P	BP	B	P	BP
GRADE	L	M	M	M	H	H

(N = no grade, L = low grade, M = medium grade and H = high grade)

PARAMETER GRADE:

SUB-PARAMETERS	DECISION RULES									
Amount of detectors	N	L	L	L	M	M	M	H	H	H
Reliability of detectors	-	L	M	H	L	M	H	L	M	H
GRADE	**0**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	**4**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_{13}. SIGNAL SYSTEM

DEFINITION: Equipment and systems for transmitting an alarm of fire

SUB-PARAMETERS:

Type of signal

Light signal (N = no, Y = yes) and Sound signal (N = no, A = alarm bell, S = spoken message)

SURVEY ITEMS	DECISION RULES					
Light signal	N	Y	N	N	Y	Y
Sound signal	N	N	A	S	A	S
GRADE	N	L	M	H	M	H

(N = no grade, L = low grade, M = medium grade and H = high grade)

Location of signal

Do you just receive a signal within the fire compartmentation or is it also possible to warn other occupants?

A	The signal is sent to the compartment only.
B	It is possible to send a signal manually to the whole building or at least to a large section of the building.

PARAMETER GRADE:

SUB-PARAMETERS	DECISION RULES						
Type of signal	N	L	L	M	M	H	H
Location of signal	-	A	B	A	B	A	B
GRADE	**0**	**1**	**2**	**3**	**4**	**4**	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

P_{14}. ESCAPE ROUTES

DEFINITION: Adequacy and reliability of escape routes

SUB-PARAMETERS:

Type of escape routes (P_{14a})

Staircase (A = one staircase may be used as an escape route, B = escape route leading to two independent staircases, C = direct escape to two independent staircases) and Window/Balcony (D = windows and balconies can not be used as escape routes, E = one window may be used as an escape route, F = at least two independent windows may be used as escape routes, G = the balcony may be used as an escape route, H = at least one window and the balcony may be used as escape routes)

SURVEY ITEMS	DECISION RULES												
Staircase	A	A	A	A	B	B	B	B	C	C	C	C	C
Window/Balcony	E	F	G	H	E	F	G	H	D	E	F	G	H
GRADE	0	1	1	3	2	3	3	4	4	5	5	5	5

(Minimum grade = 0 and maximum grade = 5)

Dimensions and layout (P_{14b})

Maximum travel distance to an escape route (A < 10 m, B = 10 – 20 m, C > 20 m), Number of floors (D ≤ 4, E = 5 – 8) and Maximum number of apartments per floor connected to an escape route (F ≤ 4, G ≥ 5)

SURVEY ITEMS	DECISION RULES											
Travel distance to	C	C	C	C	B	B	B	B	A	A	A	A
Number of floors	E	E	D	D	E	E	D	D	E	E	D	D
Number of apartments	G	F	G	F	G	F	G	F	G	F	G	F
GRADE	0	1	2	2	3	3	4	4	4	4	5	5

(Minimum grade = 0 and maximum grade = 5)

Equipment (P_{14c})

Guidance signs (A = none, B = normal, C = illuminating light), General lighting (D = manually switched on, E = always on) and Emergency lighting (F = not provided, G = provided)

SURVEY ITEMS	DECISION RULES											
Guidance signs	A	A	A	A	B	B	B	B	C	C	C	C
General lighting	D	D	E	E	D	D	E	E	D	D	E	E
Emergency lighting	F	G	F	G	F	G	F	G	F	G	F	G
GRADE	0	3	3	4	2	4	3	4	2	4	3	5

(Minimum grade = 0 and maximum grade = 5)

Linings and floorings (P_{14d})

This refers to the worst lining or flooring class that is to be found in an escape route (excluding the small amounts allowed by building law). For Euroclasses A1, A2 and B, the flooring must have at least class D_f, if not the linings and floorings grade is according to Euroclass C.

LINING CLASS						GRADE
Suggestions to Euroclasses	**Typical products**	**DK**	**FIN**	**NO**	**SWE**	
A1	Stone, concrete	A	1/I	In1	I	5
A2	Gypsum boards	A	1/I	In1	I	5
B	Best FR woods (impregnated)	A	1/I	In1	I	4
C	Textile wall cover on gypsum board		1/II 2/-	In2	II	3
D	Wood (untreated)	B	1/-	In2	III	2
E	Low density wood fiberboard	U	U	U	U	1
F	Some plastics	U	U	U	U	0

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_{14} is:

(0.34 x Type of escape routes + 0.27 x Dimension and layout + 0.16 x Equipment + Linings and floorings) =

Resulting grade:

P_{15}. STRUCTURE - LOAD-BEARING

DEFINITION: Structural stability of the building when exposed to a fire

SUB-PARAMETERS:

Load-bearing capacity (P_{15a})

LOAD BEARING CAPACITY (LBC)	GRADE
LBC < R 30	0
R 30 ≤ LBC < R 60	2
R 60 ≤ LBC < R 90	4
R 90 ≤ LBC	5

(Minimum grade = 0 and maximum grade = 5)

Combustibility (P_{15b})
Combustible part of the load-bearing construction

COMBUSTIBLE PART	GRADE
Both load-bearing structure and insulation are combustible	0
Only the insulation is combustible	2
Only the load-bearing structure is combustible	3
Both load-bearing structure and insulation are non-combustible	5

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_{15} is:

(0.74 x Load-bearing capacity + 0.26 x Combustibility) =

Resulting grade:

P_{16}. MAINTENANCE AND INFORMATION

DEFINITION: Inspection and maintenance of fire safety equipment, escape routes etc. and information to occupants on suppression and evacuation

SUB-PARAMETERS:

Maintenance of fire safety systems i.e. detection, alarm, suppression and smoke control system **(P_{16a})**

MAINTENANCE OF FIRE SAFETY SYSTEMS	GRADE
Carried out less than every three years	0
Carried out at least once every three years	2
Carried out at least once a year	4
Carried out at least twice a year	5

(Minimum grade = 0 and maximum grade = 5)

Inspection of escape routes (P_{16b})

INSPECTION OF ESCAPE ROUTES	GRADE
Carried out less than every three years	0
Carried out at least once a year	1
Carried out at least once every three months	3
Carried out at least once per month	5

(Minimum grade = 0 and maximum grade = 5)

Information to occupants on suppression and evacuation **(P_{16c})**

Written information (A = no information, B = written information on evacuation and suppression available in a prominent place in the building, C = written information available in a prominent place and distributed to new inhabitants) and

Drills (D = no drills, E = suppression drill carried out regularly, F = evacuation drill carried out regularly, G = suppression and evacuation drills carried out regularly)

SURVEY ITEMS	DECISION RULES											
Written information	A	A	A	A	B	B	B	B	C	C	C	C
Drills	D	E	F	G	D	E	F	G	D	E	F	G
GRADE	0	1	1	2	1	3	3	4	2	4	4	5

(Minimum grade = 0 and maximum grade = 5)

PARAMETER GRADE:

The Calculation and Result for P_{16} is:

(0.40 x Maintenance of fire safety system + 0.27 x Inspection of escape routes + 0.33 x Information) =

Resulting grade:

P_{17}. VENTILATION SYSTEM

DEFINITION: Extent to which the spread of smoke through the ventilation system is prevented.

PARAMETER GRADE:

TYPE OF VENTILATION SYSTEM	GRADE
No specific smoke spread prevention through the ventilation system	**0**
Central ventilation system, designed to let smoke more easily into the external air duct than ducts leading to other fire compartments. The ratio between pressure drops in these ducts is in the order of 5:1	**2**
Ventilation system specially designed to be in operation under fire conditions with sufficient capacity to hinder smoke spread to other fire compartments	**3**
Ventilation system with a non return damper, or a smoke detector controlled fire gas damper, in ducts serving each fire compartment.	**4**
Individual ventilation system for each fire compartment	**5**

(Minimum grade = 0 and maximum grade = 5)

Resulting grade:

Results: In the following table the results from the fire risk index method are summarized for a timber – frame multistory apartment building

Parameter	Weight	Grade	WEIGHTED GRADE
P1	0.0576	5	0.2880
P2	0.0668	**0**	0.0000
P3	0.0681	**3.62**	0.2465
P4	0.0666	**2**	0.1332
P5	0.0675	**3.44**	0.2322
P6	0.0698	**2.66**	0.1857
P7	0.0473	**2**	0.0946
P8	0.0492	**1.69**	0.0831
P9	0.0515	**1**	0.0515
P10	0.0396	**2**	0.0792
P11	0.0609	**2**	0.1218
P12	0.0630	**2**	0.1260
P13	0.0512	**3**	0.1536
P14	0.0620	**2.83**	0.1755
P15	0.0630	**3.74**	0.2356
P16	0.0601	**0**	0.0000
P17	0.0558	**2**	0.1116
Sum	1.0000		
		SCORE ⇒	**2.3181**

Risk Index	**2.32**

Annex D:

Example of application (Appendix 4) [34]

from “Use of Fire Safety Engineering and Risk Analysis in Cultural Heritage Buildings”

Author: Tomas Rantatalo and Fredrik Nystedt, Sweden

In this appendix you will find an example of application on using risk analysis in fire safety engineering for cultural heritage. The example should be considered only as an example and the input data and results provided here are not to be used in any other applications.

1. Fire Safety Inspection and Survey

1.1 Building design and use

The building is a 19th century post office building with one floor. The building is divided into three major areas – mail sorting room, administration office and pay office. The building is protected under the cultural heritage act as it has a unique construction with timber framed load-bearing structures. The building has been carefully renovated in the 1980s allowing it to be used as a modern post office, but the original construction has been kept unaffected.

The total floor area of the building is app. 200 m^2. The ceiling is sloped with a maximum height of 5 m and a minimum height of 3 m. The L-shape post office has one exit from the pay office, and one direct exit to the outside from both the administration office and the mail sorting room. These two areas could also use each other’s exits.

1.2 People

There are not many people in the post office. The maximum number of customers is 15-20. In addition to this, there are 2 people working as cashiers, 4 people at the administration and 4 postmen in mail sorting. All people are expected to be familiar with the escape routes. The staff is trained in fire safety on a bi-annual basis. The training involves the use of portable extinguishers, fire preventive measures and escape.

1.3 Fire safety measures

The building does not have and particular fire safety measures.

The claddings and surface finished are combustible

The fire rating of the combustible load-bearing structure is assumed to be between 15-20 min.

There is no fire rated separation between different areas in the building.

2. Fire Safety Engineering Assessment

Since the building is of great importance to the cultural heritage of the post office history, the preserver has expressed his concern that the building lacks fire safety installations. A recent fire in a similar building resulted in a total irreversible damage to the building.

A design team is brought together with the aim of analysing the fire risk in the building. The objective of the analysis is to identify the fire safety level in the post office, aiming at supporting the decision whether or not additional fire safety measures are required.

It is decided that two fire safety alternatives should be evaluated. The first alternative is to install smoke detectors with direct connection to the fire brigade. The second alternative is to install an automatic fire sprinkler system.

2.1 Level of analysis

The prescriptive building code is mainly concerned of people's safety and the protection of adjacent properties. It does not consider the special needs on property protection that a building that belongs to the cultural heritage could have.

Since the preserver is interested in the actual fire risk, it is necessary to conduct a quantitative analysis. A quantitative analysis is a sound basis in decision-making in fire safety engineering. It enables the management to clearly see the benefits from an installation before deciding on it.

A quantitative risk analysis based on event tree technique will be used to model the possible scenarios that could be the outcome of an initial fire.

2.2 Fire scenarios and design fires

National statistics points out a few major causes of ignition. The most frequently cause is faulty electrical wiring. Another common cause of ignition is malfunctioning fluorescent lamps. During the FSIS it was found that portable heaters was commonly used during the cold month of the year. Based on the building plan and the information on ignition sources, two fire scenarios are considered.

- Fire in the mail sorting room
- Fire in the administration office

The design fire in the mail sorting room involves a fire that starts when a pile of mailbags is placed to close to a portable heater. Heat release data on mailbags is found in Karlsson et al [35]. A pile of mailbags of 5 feet develops 400 kW/m^2 and has a fast fire growth rate. The initial fire will be in such a pile of mailbags, but as the fire develops it will have the potential to spread to other piles as well.

The fire in the administration office is caused by a faulty fluorescent lamp that leaks hot oil into a trash bag. Figure 0.1 shows heat release data for trash bags.

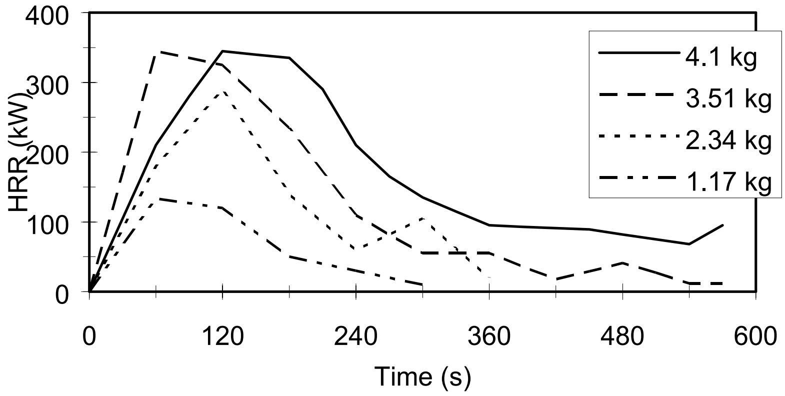


Figure 0.1 Heat release data for trash bags, adopted from Babrauskas (1995).

The trash bag in the office has a weight of 1.2 kg and shows a medium fire growth rate with a maximum heat release rate of 140 kW. The fire will however be able to spread to other combustibles in the room like curtains, bookshelves, chairs, etc.

The two fire scenarios and their design fires are described more detailed below.

- Mail sorting room: The fire will grow at a fast (0.047 kW/s^2) growth rate to a maximum heat release rate of 2 MW. After 5 min it will spread to two other pile of mailbags, adding another 4 MW of fire development. The fire spread will continue in this manner until flashover conditions occur.
- Administration office: The fire will grow at a medium rate (0.012 kW/s^2). The initial maximum heat release of 140 kW will stand for app. 3 min, after which the fire is considered to spread to curtains and shelves developing another 2 MW with a fast fire growth. The office is a small room, where engineering calculations shows a maximum possible heat release rate of 3 MW. The fire in the office will therefore soon become ventilation controlled.

2.3 Objectives, acceptance criteria and design parameters

The life safety objectives of people in the building are considered fulfilled without any further analysis. The total number of people in the building is less than 30, and there is a satisfactory number of escape routes, according to the prescriptive code.

The fire safety objective in need for evaluation is the protection of property. The overall objective is that no (or very limited) irreversible damage should be caused to the building in the event of fire. Based on this objective the following acceptance criteria is established.

- When all safety systems are working as intended, there should be less than 5 % irreversible damage to the building, i.e. 10 m^2.
- The probability of having irreversible damage to more than 25 % of the building, i.e. 50 m^2 should be less than 10 % given a developing fire.

It is the load-bearing structure of timber that is most importantly to protect from fire. Irreversible damage is defined to occur if the temperature at the structure exceeds the ignition temperature of wood, i.e. 300 °C.

3. Risk Analysis

3.1 Selection of events

The acceptance criteria are based on the event that a developing fire will occur. By this it is meant that events like fire starts and fire self-extinguished will not be considered. The initial event is therefore the developing fire and the following intermediate events are proposed.

Developing fire → Fire location → Time of day → Fire detected → Extinguished by staff → Sprinkler control the fire → Fire brigade control the fire.

<u>Fire location</u>

The fire could be located either in the mail sorting room or in the administration office. The probability of having a fire in either of the locations is related only to the floor area. The total floor area of office and the sorting room is 150 m^2, where 64 m^2 is in the office and 96 m^2 is the sorting room.

- The probability of fire in the mail sorting room is 96/150 = 0.64.
- The probability of fire in the mail sorting room is 64/150 = 0.36.

<u>Time of day</u>

Fire statistics show that most fires in post office buildings starts during daytime, when there are activities in the building.

- The probability of a daytime fire is 0.70.
- The probability of fire at night is 0.30.

<u>Fire detected</u>

The fire could be detected either manually or automatically by the smoke detectors. It is considered that automatic detection will be the only possibility to detect a fire during the night. This event should be interpreted as the fire is detected soon enough to enable a extinguishing effort by the staff.

- The probability of detecting a fire without having smoke detectors installed is 0.50 during the day and 0.00 during the night.
- The probability of detecting a fire when smoke detectors are present is 0.90, independent of which time of the day that the fire occurs.

Extinguished by staff

The event does only take place during daytime fires and if the fire is successfully detected. If the staff is able to control the fire, this branch in the tree will not continue. If not, it's up to the sprinkler system if such is present.

- The probability of the fire being extinguished by the staff is 0.60, based on finding from previous fires and the staff's level of training.

Sprinkler control the fire

If the sprinkler control the fire the branch will jot continue if the sprinkler system successfully controls the fire. If not, it's up to the fire brigade. Sprinklers operate successfully with a probability of 92-97 %.

- A conservative estimate of the probability that the sprinkler control the fire of 0.92 is used in the analysis.

Fire brigade control the fire

If the fire is controlled by the fire service the damage will not extend beyond the area where it was when the fire service's operation began to be effective. If the fire service is unsuccessful in their extinguishing attempts the fire will be limited to specific fire cell or to the whole building. The probability of having the fire brigade controlling the fire is found in statistics.

- The fire brigade is considered to successfully control the fire with a probability of 0.80.

3.2 Event tree design

The analysis treats three different event trees, as there are three different fire safety alternatives. The information provided in section 3.1 is used to design the event trees shown in

Figure 0.2-

Figure 0.4 below.

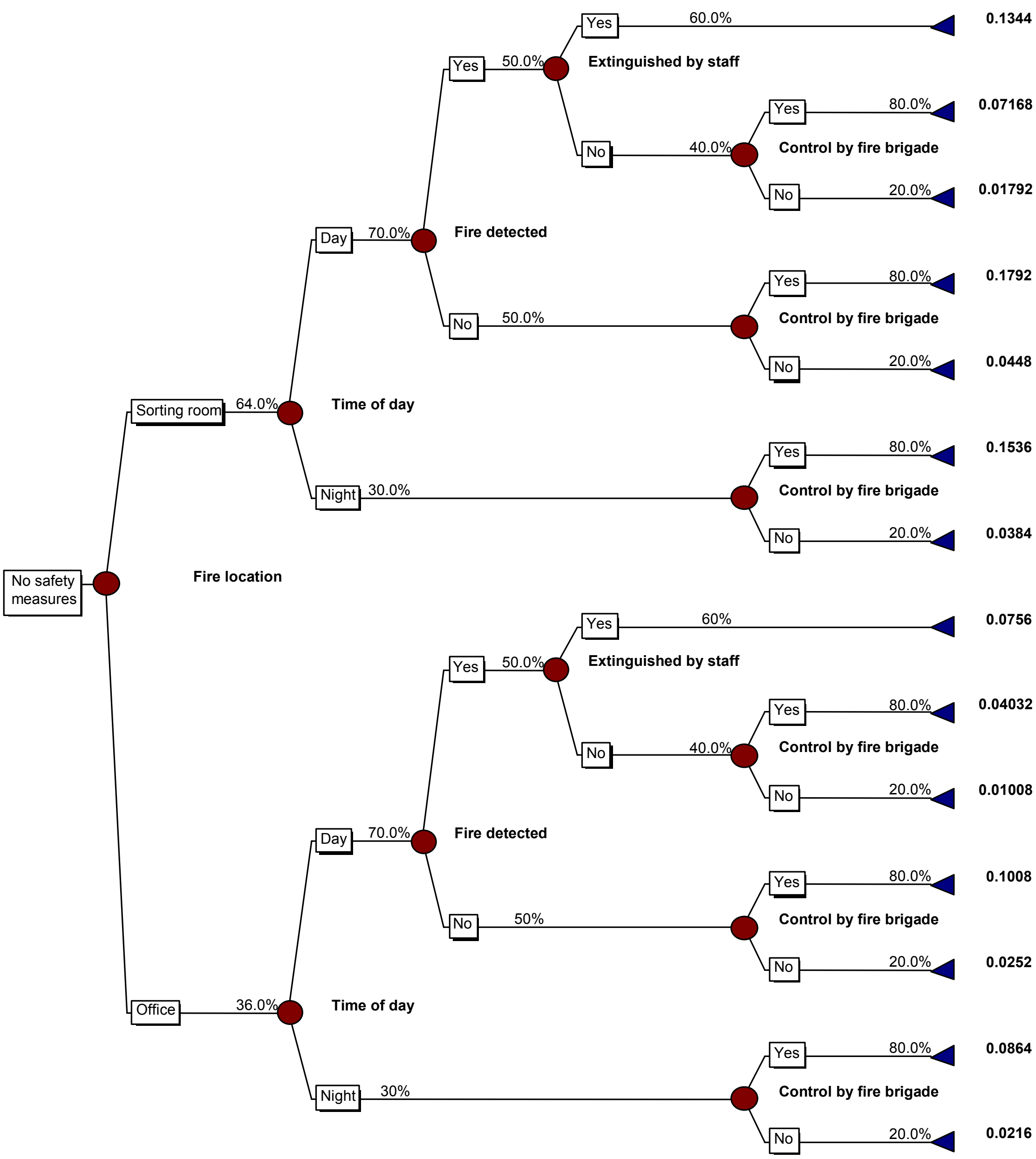


Figure 0.2 Event tree for post office fire. No fire safety measures.

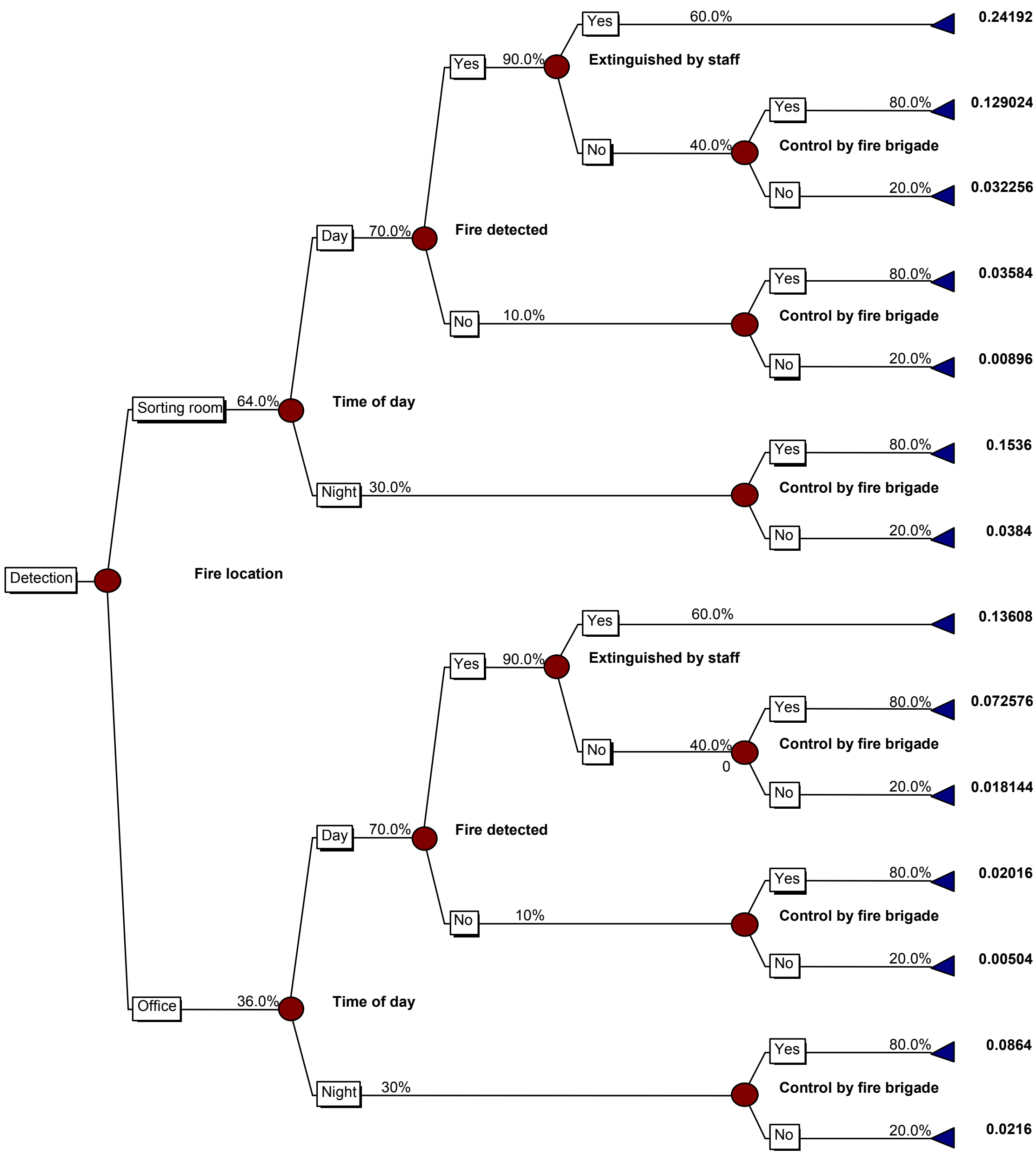


Figure 0.3 Event tree for post office fire. Smoke detectors.

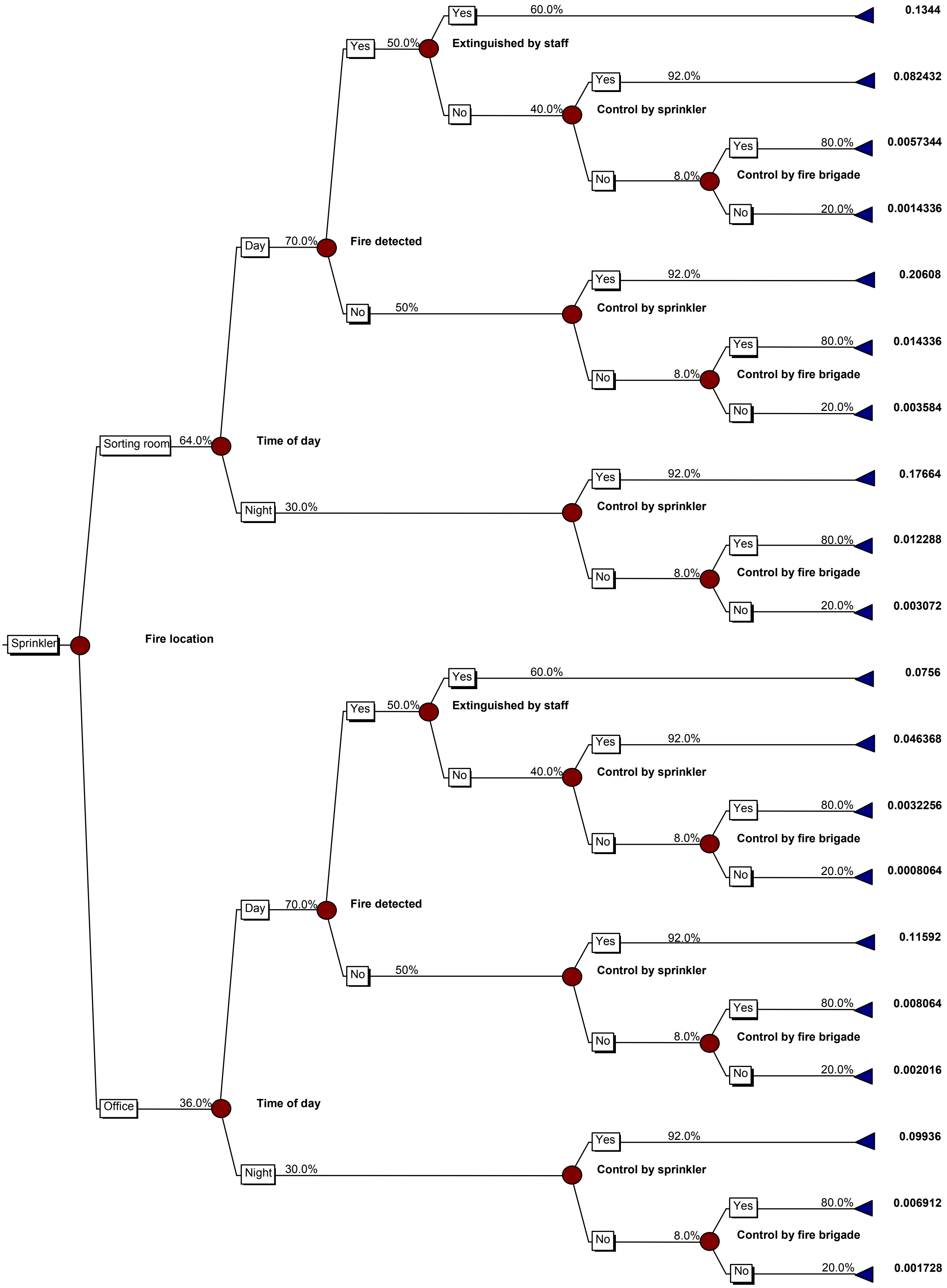


Figure 0.4 Event tree for post office fire. Sprinkler system.

3.3 Quantification of fire development

Fire in mail sorting room

The fire development in the mail sorting room is shown in Figure 0.5 as a function of fire spread over time. Fire spread is assumed to happen when the ignition temperature of wood (300° C) is exceeded.

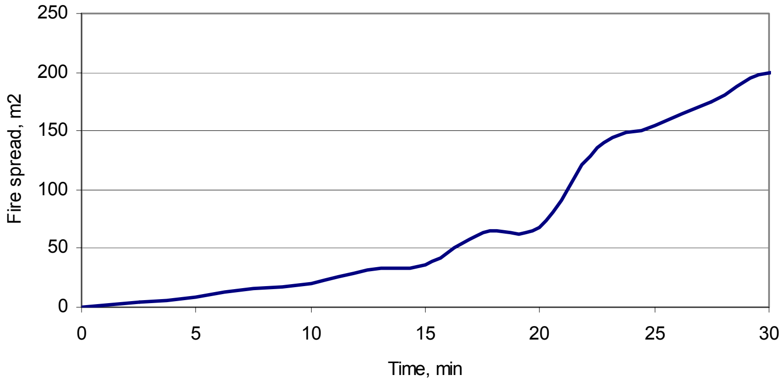


Figure 0.5 Fire development in mail sorting room fire.

Considering the flame spread and the radiation to boundaries derives the information used to assess the fire spread (Figure 0.5). This information could be made available by the use of hand calculation equations for more simple structures and by the use of CFD models for more complex buildings. Hand-calculation equations are used to evaluate the flame spread rate and to assess radiation levels to walls and ceilings as the fire develops. The radiation level can be translated to a surface temperature if the boundary materials are known. When CFD-models are used the information on boundary temperature is easily available. Figure 0.6 shows an animation from a CFD simulation.

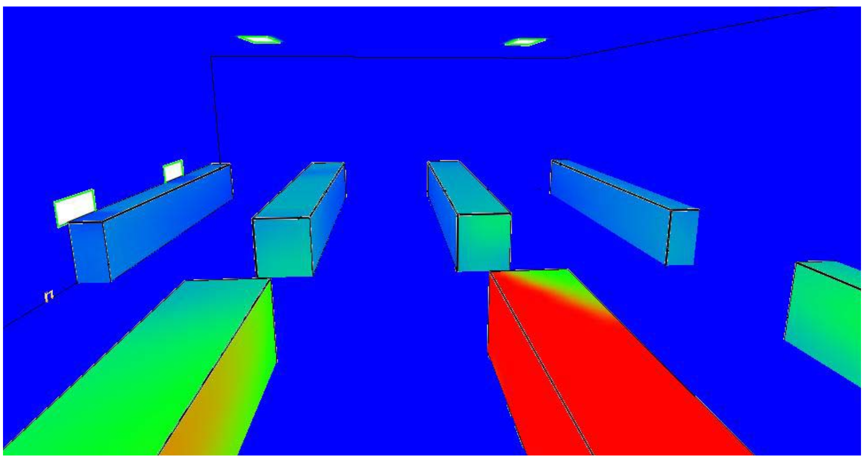


Figure 0.6 Output from CFD simulation, used to assess fire damage area.

Fire in administration office

The fire development in the administration office is shown in Figure 0.7. The fire spread has been assessed as outlined above.

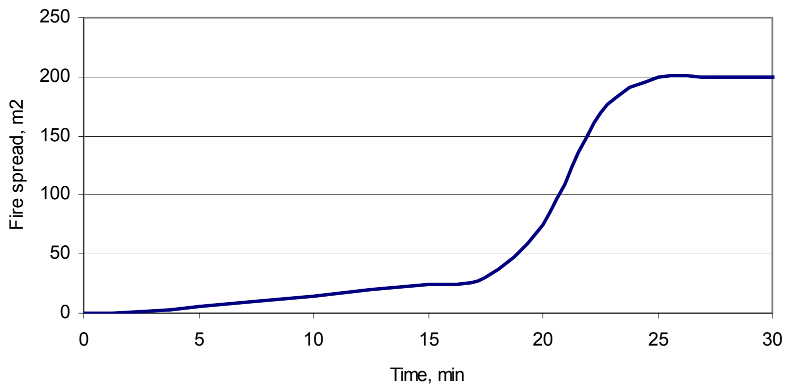


Figure 0.7 Fire development in administration office fire.

3.4 Assessment of damage

Damage occurs when the temperature exceeds 300° C. Figure 0.5 and Figure 0.7 above show when this occurs for the two fire scenarios. The event trees show that there are several measures that could prevent the whole building from being involved in the fire. These events are extinguished by staff, controlled by sprinkler or controlled by fire brigade.

Fire in mail sorting room

It will take the staff app. 2.5 min to extinguish the fire, resulting in a damage area of 5 m^2. The sprinkler system activates after 4 min and limiting the fire to 8 m^2. The local fire brigade will be able to control the fire development app. 15 min after it has begun its development. The damage area in this case will be 36 m^2. If the fire brigade is unsuccessful, the whole building will burn down.

Fire in administration office

The time for staff response is the same as for the sorting room fire resulting in a damage area of 2 m^2. The sprinkler system will activate after 5 min, due to the medium fast growth rate. The damage area is 6 m^2. Successful fire fighting operation from the fire brigade limits the fire area to 25 m^2. Non-successful operation will cause damage to the whole building.

3.5 Calculation of risk measures

The event tree technique enables easy access to three different risk measures. These are probability of damage, average risk and risk profile. The procedure of calculating these measures is outlined in section 3.2.5 of the main report [31]. The procedure for the calculation of risk measures is illustrated for one of the alternatives “no safety measures” below.

First a list of all scenarios (with respect to the event tree in
Figure 0.2) is derived and the probability and the consequence is presented for each scenario. This list is shown in Table 0.1.

Table 0.1 List of scenarios with their respective probability and consequence.

Scenario	State	Prob.	Cons., m^2
1	Extinguished by staff	0.1344	5
2	Control by fire brigade	0.07168	36
3	Total damage	0.01792	200
4	Control by fire brigade	0.1792	36
5	Total damage	0.0448	200
6	Control by fire brigade	0.1536	36
7	Total damage	0.0384	200
8	Extinguished by staff	0.0756	2
9	Control by fire brigade	0.04032	25
10	Total damage	0.01008	200
11	Control by fire brigade	0.1008	25
12	Total damage	0.0252	200
13	Control by fire brigade	0.0864	25
14	Total damage	0.0216	200

The nest step is to sort the scenarios in descending order by consequence and to calculate the cumulative probability of X or more fire damage. This is shown in Table 0.2.

Table 0.2 Sorting scenarios in descending order by consequence.

Scenario	State	Prob.	Cumul. prob.	Cons., m^2
3	Total damage	0.01792		200
5	Total damage	0.0448		200
7	Total damage	0.0384		200
10	Total damage	0.01008		200
12	Total damage	0.0252		200
14	Total damage	0.0216	0.158	200
2	Control by fire brigade	0.07168		36
4	Control by fire brigade	0.1792		36
6	Control by fire brigade	0.1536	0.56248	36
9	Control by fire brigade	0.04032		25
11	Control by fire brigade	0.1008		25
13	Control by fire brigade	0.0864	0.79	25
1	Extinguished by staff	0.1344	0.9244	5
8	Extinguished by staff	0.0756	1.0	2

The information in Table 0.2 is then used to draw the risk profile shown in Figure 0.8. Since all scenarios results in a consequence the probability of damage to the building is 1.0. The average risk of damage, R $_{avg}$ is calculated by the following expression.

$$R_{avg} = \sum_{i=1}^{n} p_i \cdot c_i$$

Where i is each individual scenario and p_i and c_i is the probability and the consequence to each scenario. Table 0.3 shows the probability of damage and the average risk for the three fire safety design alternatives and Figure 0.8 shows their risk profiles.

Table 0.3 Risk measures for the three fire safety alternatives, given developing fire.

Alternative	Probability of damage	Average risk
No safety measures	1.00	53 m^2
Smoke detection	1.00	42 m^2
Sprinkler system	1.00	10 m^2

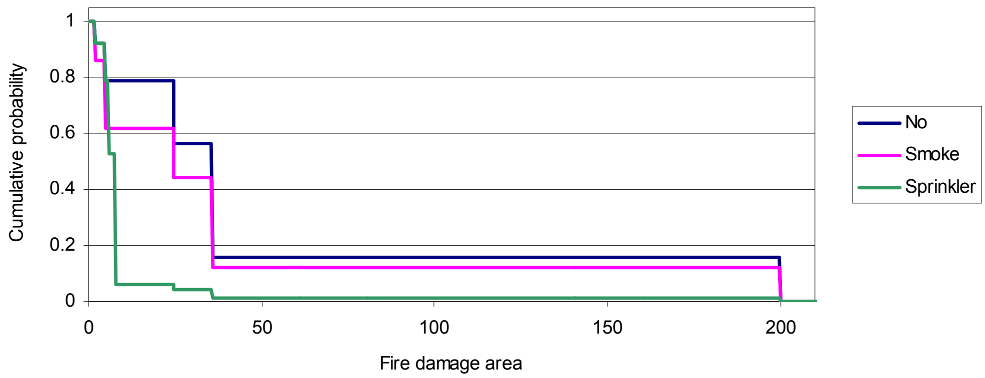


Figure 0.8 Risk profiles for the three fire safety alternatives, given developing fire.

3.6 Risk evaluation

The two acceptance criteria that were decided on in the FSEA are that there should be no greater damage than 10 m^2 if everything is going as intended and that the probability of having a damage of 50 m^2 should be less than 10 %.

All the three fire safety alternatives fulfill the first criterion. The damage area is limited to 2-5 m^2 when all system operates as intended. The probability of having fire damage greater than 50 m^2 is 16 % if there are no safety measures, 12 % if the building is equipped with smoke detectors and 1 % if the building has a sprinkler system installed. It is only the sprinkler that fulfils the second criterion.

It is recommended that the post office should be equipped with a sprinkler system.

Annex E:

A Probabilistic Method for Optimization of Fire Safety in Nuclear Power Plants

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Abstract

As part of a comprehensive fire safety study for German Nuclear Power Plants probabilistic method for the analysis and optimisation of fire safety has been developed. It follows the general line of the American fire hazard analysis, with more or less important modifications in detail. At first, fire event trees in selected critical plant areas are established taking into account active and passive fire protection measures and safety systems endangered by the fire. Failure models for fire protection measures and safety systems are formulated depending on common parameters like time after ignition and fire effects. These dependences are properly taken into account in the analysis of the fire event trees with the help of first-order system reliability theory. In addition to frequencies of fire-induced system failures relative weights of event paths, fire protection measures within these paths and parameters of the failure models are calculated as functions of time. Based on these information optimisation of fire safety is achieved by modifying primarily event paths, fire protection measures and parameters with the greatest relative weights. this procedure is illustrated using as an example a German 1300 MW PWR reference plant. It is shown that the recommended modifications also reduce the risk to plant personnel and fire damage.

INTRODUCTION

From 1982 to 1984 a comprehensive theoretical and experimental study on fire safety in nuclear power plants /1/ was conducted by several German research institutes. The work was sponsored by the Federal Minister of the Interior (BMI) and was coordinated by the Gesellschaft für Reaktorsicherheit (GRS).

One of the main aims of the study was the development of a method for analysing quantitatively fire hazards in critical plant areas in order to

- compare the fire risk with the risk due to other internal or external events
- detect weak points in fire safety concepts
- reduce fire risk by more efficient combinations of fire safety measures
- make fire safety measures more efficient by influencing the most important parameters.

At the beginning, American methods for fire hazard analysis /2/ and fire risk analysis (e. g. /3, 4/) were studied. These methods seemed to be less appropriate for German nuclear power plants because

- the German fire safety concept is mainly based on physical separation of systems and less on fire suppression measures
- the fire effects on fire protection measures and safety systems are not explicitly taken into account
- the dependences between single failures due to the time-dependent fire effects are not clearly treated in the event tree analyses.

Therefore, a somewhat modified methodology based on first-order reliability theory was developed consisting of:

- the assessment of time-dependent fire event trees
- the definition of simplified failure models for fire protection measures and safety systems to be used in reliability analyses
- the analysis of the fire event trees with the help of first-order system reliability methods
- the optimisation of fire protection measures based on the results of the event tree analyses.

The latter two steps will be illustrated using as an example a German 1300 MW PWR reference plant.

TIME-DEPENDENT FIRE EVENT TREES

The risk-orientated investigations in /1/ started with the selection of areas in a typical German PWR plant, in which potential fire hazards could endanger safety systems or plant personnel. For these areas event sequences induced by the occurrence of an initial fire were established. Similar to /2/ different protective measures are provided to detect and suppress a fire or to limit the effects of a fire on safety systems and personnel to the compartment affected (Fig. 1). From experience the most probable times of actuation (after ignition) with lower and upper bounds can be estimated for all active fire protection measures.

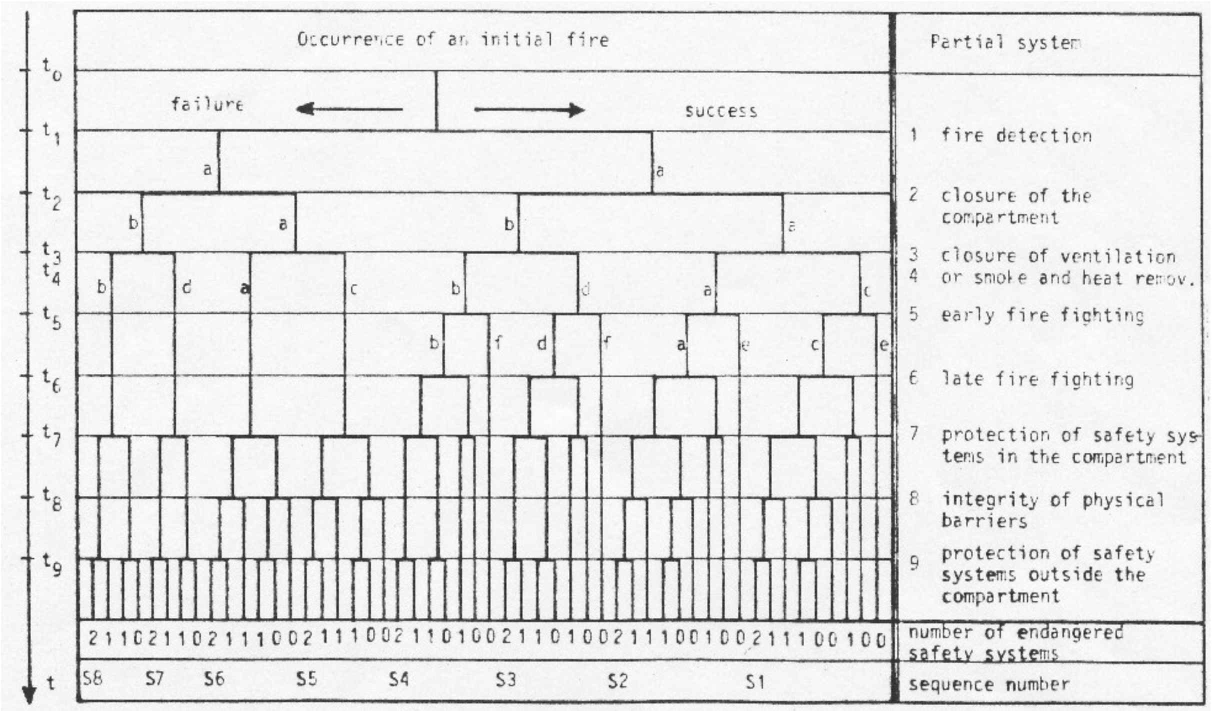

Fig. 1 time-dependent fire event tree

Depending on success or failure of the active fire protection measures different time-histories of fire effects are expected. In Fig. 2 a set of temperature-time-histories is shown with the following boundary conditions:

curve a – normal conditions, compartment closed, fixed forced ventilation rate, not fire suppression
curve b – at least one door open (higher ventilation rate), no fire suppression
curve c – like a, but ventilation stopped at time t_3
curve d – like b, but ventilation stopped at time t_3
curve e – like a, but fire suppression started at time t_5
curve f – like b, but fire suppression started at time t_5 .

If fire suppression measures are properly designed and actuated in due time the temperature decrease is so fast that curves e and f can be neglected in the analysis of consequences.

One of the above mentioned temperature-time-histories is assigned to each branch of the event tree in Fig. 1. Depending on the respective temperature at the time of demand failures of fire protection measures of safety systems due to fire can occur. Therefore, the consequences of a fire in a plant area depend on time, too. In the analysis of the event tree the frequencies of critical consequences, e. g. failure of one redundancy of safety systems in the fire compartment and failure of a physical barrier between two compartments and failure of a second redundancy in the adjacent compartment, are checked at varying time steps t*.

FAILURE MODELS FOR FIRE PROTECTION MEASURES AND SAFETY SYSTEMS

In order to account for dependences due to the time-dependent fire effects the single failures are described with the help of simplified mechanical models. The models are constructed as follows:

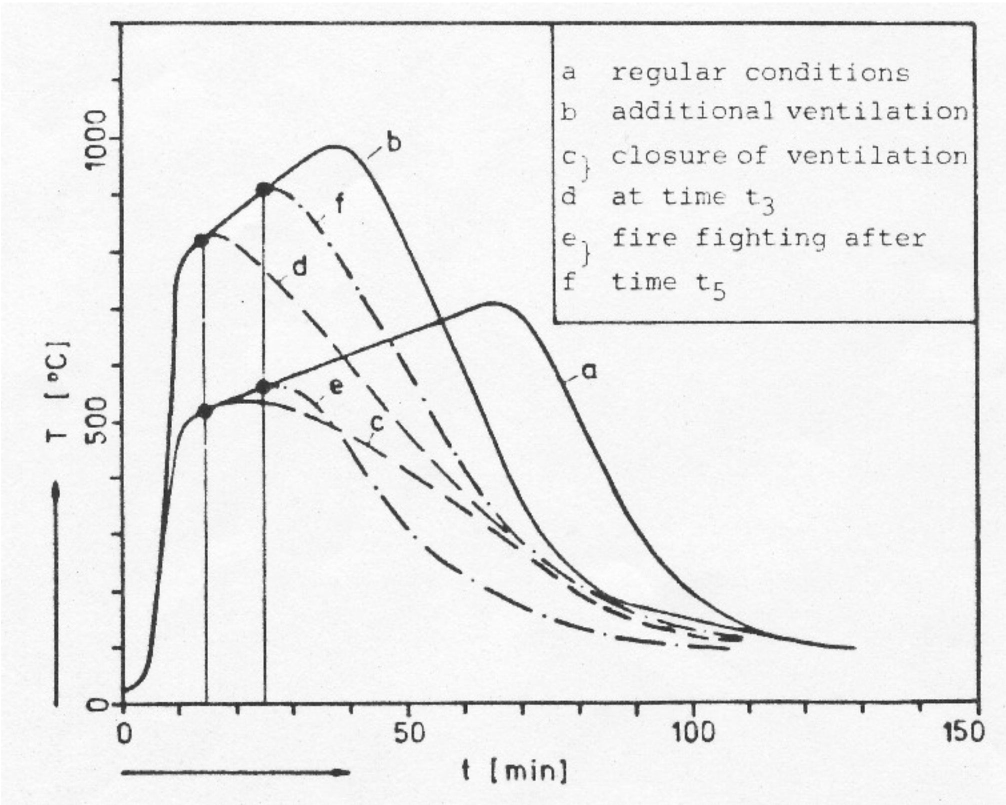

Fig. 2 Typical temperature-time-histories in NPP compartments

The active fire protection measures are divided in 6 "partial systems" as indicated in Fig. 1:

- fire detection and alarm
- closure of openings in the compartment boundary
- closure of shut down of compartment ventilation
- removal of smoke and heat
- early fire fighting inside the compartment
- late fire fighting from outside the compartment.

These partial systems are composed of “components” which act in parallel or series arrangements. The failure frequencies of the partial systems can be derived from failure rates of the components using fault tree models (e. g. Fig. 3).

Failure rates of the “components” are only partly known from statistical data. Especially, the portion of failures due to fire or late actuation is not sufficiently well covered by data. Therefore, simplified limit-state models are formulated and treated with the help of first-order reliability theory. For the partial system “early fire fighting” shown in Fig. 3, the limit-state functions are as follows:

$p_{51} = P\{Z_{51} \leqq -ß_{51}\}$

$ß_{51}$ = standardized Gaussian variable calibrated with statistical data for p_{51}

$p_{52} = P\{Z_{52} \leqq -ß_{52}\}$

$ß_{52}$ = analogical to $ß_{51}$

$p_{53} = P\{Z_{53} \leqq T_{RM} - T(t_5)\}$

T_{RM} = ultimate temperature (°C) for manual fire suppression
$T(t_5)$ = gas temperature (°C) at time t_5
$t_5 = t_1 + \Delta t_5$
= time of fire detection + delay from detection to arrival of fire emissary

$p_{54} = P\{Z_{54} \leqq -ß_{54}\}$

$ß_{54}$ = analogical to $ß_{51}$

$p_{55} = P\{Z_{55} \leqq T_{RL} - T(t_5)\}$

T_{RL} = ultimate temperature (°C) for fire suppression system

$p_{56} = P\{Z_{56} \leqq -ß_{56}\}$

$ß_{56}$ = analogical to $ß_{51}$

$P_{57} = P\{Z_{57} \leqq t^* - t_5 - \Delta t_5^*\}$

t^* = varying time for checking the consequences

Δt_5^* = duration of fire fighting until success.

The failure frequencies of passive fire protection measures (physical barriers) and safety systems depend strongly on fire effects, especially on gas temperature, which are functions of the time after occurrence of the initial fire.

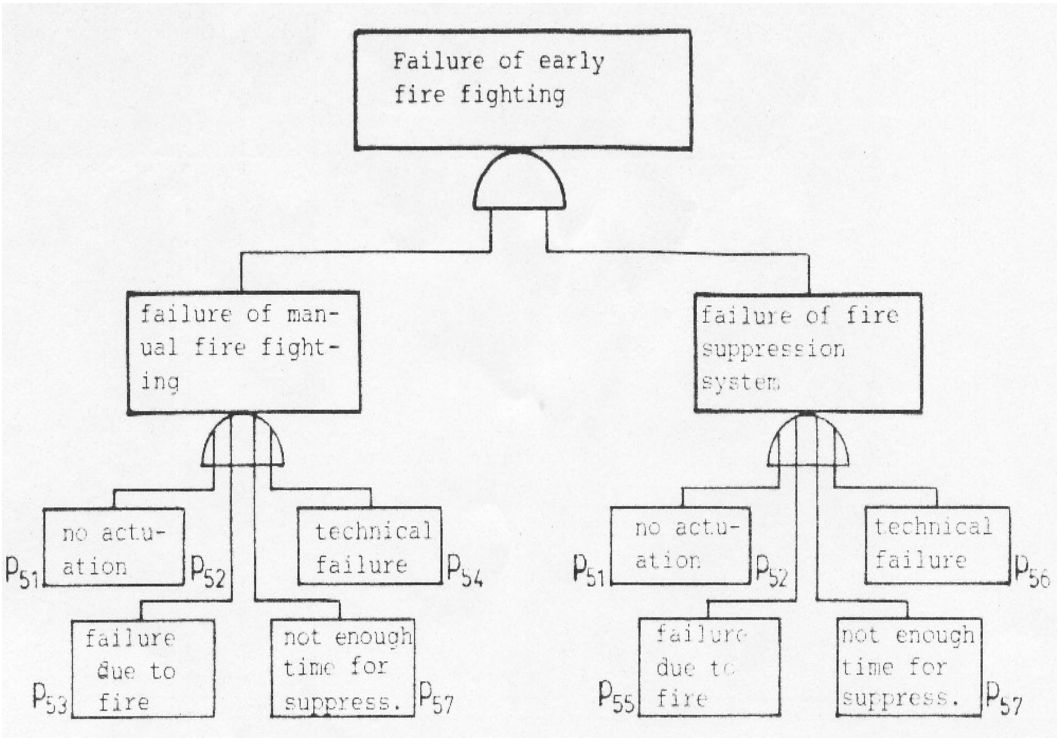

Fig. 3 Fault tree for failure of early fire fighting within the compartment

For safety systems (mechanical and electrical components) ultimate gas temperatures have to be specified during design, based on fire test or experience. Passive fire protection measures are usually tested in standard fire tests, e. g. in Germany according to DIN 4102 /6/. the fire resistance of these measures does not only depend on the gas temperature but also on the time of action of the temperature; therefore, the time-integral of the standard fire curve up to the fire resistance time is taken as ultimate limit of fire resistance. In /1/ it was shown that this ultimate limit is valid not only for standard fires but also for natural fires in the compartments under consideration (cf. /7/).

All limit-state definitions used for the “components” of active fire protection measures as well as for passive fire protection measures and safety systems are summarized in Tab. 1. The parameters influencing the limit-states are random variables which are described by distribution parameters (cf. Tab.2). The limit-states are dependent, due to common parameters.

SYSTEM RELIABILITY ANALYSIS

The fire event tree in Fig. 1 can be treated like a technical system consisting of the different event sequences with the same consequence in series arrangement. Within each event sequence the partial systems according to the preceding section are arranged in parallel. Finally, the partial systems act as parallel or series system with several “components”. The state of the overall system can be formulated with the help of Boolean algebra. Alternatively, the system state can be directly related to the states of the individual “components” or it can be determined indirectly using intermediate systems (i. e. event sequences) or partial systems as a kind of macro-components).

In the following, mainly the second “subsystem method” is used because of its advantages with respect to calculation effort and interpretation of the results. Because of the above mentioned dependences between some of the single components the classical methods for fault tree and event tree analysis are not applicable; i. e. the frequencies of the overall system state cannot be calculated by multiplying (for intersections) or summing up (for unions) the component or macro-component state frequencies. Therefore, first-order system reliability methods are used which are based on proposals in /7-10/. Only very few aspects of these methods can be discussed here.

Tab. 1 Limit-states of the event tree in Fig. 1

limit state				partial system	
no.	name	failure for $Z_i \leq 0$	fire curve	no.	function
1	Z_{11}	no manual direct fire detection			
2	Z_{12}	no automatic fire detection			
3	Z_{13}	no manual indirect fire detection		1	fire detection
4	Z_{14}	no automatic indirect fire detection			
5	Z_{15}	no indirect fire detection through failure of components			
6	Z_{21}	Opening in physical separation not closed			
7	Z_{22}	no automatic closure		2	physical separation of the compartment
8	Z_{23}	technical failure			
9	Z_{24}	no manual closure			
10	Z_{31}	no closure of the air ventilation through personnel			
11	Z_{32}	no closure of the air ventilation through fire emissary			
12	Z_{33}	no closure of the air ventilation from the control room			
13	Z_{34a}	no automatic closure of the air ventilation	a	3	closure of the air ventilation
14	Z_{34b}		b		
15	Z_{35}	technical failure			
16	Z_{41}	no actuation of smoke and heat removal system by personnel			
17	Z_{42}	no actuation of smoke and heat removal system by fire emissary		4	smoke and heat removal
18	Z_{43}	no switch over of the air ventilation			
19	Z_{44}	technical failure			
20	Z_{51}	no early fire fighting through personnel			
21	Z_{52}	no early fire fighting through fire emissary			
22	Z_{53a}	failure of manual fire fighting due to fire	a		
23	Z_{53b}		b		
24	Z_{53c}		c		
25	Z_{53d}		d	5	early fire fighting in the compartment
26	Z_{54}	technical failure of the manual fire fighting			
27	Z_{55a}	failure of the fire suppression system due to fire	a		
28	Z_{55b}		b		
29	Z_{55c}		c		
30	Z_{55d}		d		
31	Z_{56}	technical failure of the fire suppression system			
32	Z_{57}	not enough time for fire suppression			
33	Z_{61}	not enough time for late fire fighting		6	late fire fighting from outside the compartment
34	Z_{64}	technical failure			
35	Z_{71a}	failure of safety systems in the compartment due to fire effects	a		
36	Z_{71b}		b	7	protection of safety systems in the compartment
37	Z_{71c}		c		
38	Z_{71d}		d		
39	Z_{81a}	failure of physical barriers due to fire effects	a		
40	Z_{81b}		b	8	integrity of physical barriers
41	Z_{81c}		c		
42	Z_{81d}		d		
43	Z_{91a}	failure of safety systems in an adjacent compartment due to fire effects	a		
44	Z_{91b}		b	9	protection of safety systems in an adjacent compartment
45	Z_{91c}		c		
46	Z_{91d}		d		
47	Z_{92}	late fire spread to an adjacent compartment or redundancy			

As shown before, the states of all single components are described by state functions Z_i (df. Tab.1) where

$Z_i \leqq 0$: failure of the component

$Z_i > 0$: success of the component.

Tab. 2 Random basic variables for the limit-states of Tab. 1

		Random variables	
no	name	significations	
1	p_{11}	failure probability of personnel in the compartment	
2	p_{12}	failure probability of automatic alarm in the compartment	
3	p_{13}	failure probability of personnel in adjacent compartments	
4	p_{14}	failure probability of automatic alarm in adjacent compartments	
5	p_{15}	probability of not recognizing component failures	
6	p_{21}	probability of physical separations being not closed	
7	p_{22}	failure probability of automatic closure	
8	p_{23}	probability of a technical failure	
9	p_{32}	probability of air ventilation being not closed by the fire emissary	
10	p_{33}	failure probability of actuation from the control room	
11	p_{35}	probability of smoke and heat removal system not being actuated by personnel	
12	p_{42}	probability of smoke and heat removal system not being actuated by f. emissary	
13	p_{43}	probability of air ventilation not being switched over	
14	p_{44}	probability of technical failure	
15	p_{54}	failure probability of manual fire fighting equipment	
16	p_{56}	failure probability of fire suppression system	
17	p_{62}	failure probability of equipment for indirect fire suppression	
18	T_L	actuation temperature of solder	
19	ΔT_A	temperature difference between compartment and exhaust air duct	
20	ΔT_Z	temperature difference between compartment and supply air duct	
21	ΔT_{KN}	temperature difference between compartment and safety system in adjacent area	
22	T_{RM}	ultimate temperature of the manual fire fighting	
23	T_{RL}	ultimate temperature of the fire suppression system	
24	T_{RK}	ultimate temperature of safety systems in the compartment	
25	T_{RKN}	ultimate temperature of safety systems in the adjacent compartment	
26	$\int T\,dt$	temperature capacity of the physical barriers	
27	T_{10}		
28	a_1		
29	a_{A1}	parameters to describe the temperature-time-history	a
30	α_{A1}		
31	t_{A1}		
32	T_{20}		
33	a_2		
34	a_{A2}	parameters to describe the temperature-time-history	b
35	α_{A2}		
36	t_{A2}		
37	a_{A3}	- " -	c
38	α_{A3}		
39	a_{A4}	- " -	d
40	α_{A4}		
41	t_1	time of fire alarm	
42	Δt_3	delay from alarm to closure of air ventilation (arrival of fire emissary)	
43	Δt_4	delay from alarm to actuation of the smoke and heat removal system	
44	Δt_5	delay from alarm to actuation of fire fighting	
45	Δt_5^*	duration of fire fighting until successful suppression	
46	Δt_6	delay from direct to indirect fire fighting	
47	Δt_6^*	duration of indirect fire fighting	
48	t_W	delay from initial fire to fire spread into an adjacent area	
49	t^*	varying time for checking the consequences of the fire	

If Z_i is a function of a parameter vector $\underline{X}$ according to Fig. 4 and each parameter is known with its probability distribution, then e. g. the probability of component failure

$$p_{fi} = P\,(Z_i\,(\underline{X}) \leqq 0) \qquad (1)$$

can be calculated by a first-order reliability method. The basic principle of the applied method is to transform the limit-state Z_i into a linear function of uncorrelated standardized Gaussian variables. Then the probability distribution Φz_i is standardized Gaussian, too and can easily be determined; the probability of failure is Φz_i ($Z_i = -ß_I$) where $ß_I$ is the so-called safety index. The contributions of the random variations of the parameters $\underline{X}_i$ to the safety index $ß_i$ are given by so-called weighting factors $ά_{Xi}$ which are calculated during linearization of the limit-state following an idea in /8/.

The weighting factors $ά_{\underline{X}i}$ are an appropriate means for identifying the relative importance of the parameters $\underline{X}_i$ for a limit-state under consideration. They help also to evaluate the degree of correlation between two limit-states Z_i and Z_j with commom parameters $\underline{X}$ because the correlation p_{ij} is simply

$$p_{ij} = \sum_{k=1}^{n} \alpha_{ik} \cdot \alpha_{jk} \qquad (2)$$

Now, the conditions for system analysis are as follows:

- All components of the system are described by state functions Z_i .
- The safety indices $ß_i$ and the weighting factors $ά_{Xi}$ have been calculated separately for each limit-state
- The correlation coefficiente p_{ij} for each couple of two limit-states Z_i and Z_j are determined with Eq. (3)
- The stated of the partial systems with components in parallel and series arrangement have to be analysed as intersections and unions of correlated component states, e. g. for failure F_5 of partial system no. 5 “early fire fighting” according to Fig. 3:

$$F_5 = \{ (Z_{51} \leqq 0) \cup (Z_{52} \leqq 0) \cup (Z_{53} \leqq 0) \cup (Z_{54} \leqq 0) \cup (Z_{57} \leqq 0) \}$$
$$\cap \{ (Z_{51} \leqq 0) \cup (Z_{52} \leqq 0) \cup (Z_{55} \leqq 0) \cup (Z_{56} \leqq 0) \cup (Z_{57} \leqq 0) \}$$

- The state of the overall system has to be evaluated as intersection of the states of different event sequences as unions of the states of the correlated partial systems, e. g. for the consequence “loss of two redundancies of safety systems” according to Fig. 1:

$$F = \{S1 \cup S2 \cup S3 \cup \ldots \cup S8\}$$

with

$$S1 = \{F_1 \cap F_2 \cap F_3 \cap F_5 \cap F_6 \cap F_7 \cap F_8 \cap F_9\}$$

To analyze the state probabilities approximate solutions of the multinormal probability integral on the basis of /9/ for intersections and /10/ for unions are applied. By using equivalent linearizations according to /7/ for partial systems, intermediate systems and the overall system, equivalent safety indices and equivalent weighting factors can be evaluated for all these systems. These values are very helpful for interpreting the results of such complex system analyses.

OPTIMIZATION OF FIRE PROTECTION MEASURES

The optimisation of fire protection measures and quality controls in nuclear power plants can have different aims, e. g.:

- minimization of the total of construction cost, control and maintenance cost and damage cost for a given fire safety level
- minimization of the frequency of fire-induced comsequences for given total cost
- reduction of the frequency of fire-induced consequences with the help of more effective fire protection measures.

Since the information on the different cost contributions was very poor the more pragmatic third aim was chosen for the optimisation in /1/. A good basis for the assessment of fire protection measures are the results of the system reliability analyses. They show clearly

- which plant area is critical with respect to the consequences of a fire for reactor safety, plant personnel or plant operation
- which protective measures really reduce the frequency of the consequences or limit the damage cost
- which parameter has the greatest influence on the efficiency of the most important protective measures.

The fire safety level in uncritical plant areas should be chosen according to conventional requirements. In critical areas a higher fire safety level seems to be reasonable in order to minimize the consequences of a fire. Fire protection measures which are expensive but unreliable should be avoided. Also protective measures without any influence on frequency or extend of consequences are unreasonable. The best way to increase the efficiency of fire protection measures is by variation of parameters with the greatest relative weight.

APPLICATION TO A REFERENCE PLANT

The methods described in the preceding sections were applied in /1/ to a German 1300 MW PWR reference plant in order i) to demonstrate the efficiency of the methodology, ii) to check the completeness of the available input data and to study the influence of uncertain data, iii) to assess the fire safety concept and identify relative weak points and iv) to derive recommendations for the optimisation of fire protection measures and related quality controls.

For all selected plant areas the frequencies p_f of critical fire-induced consequences were calculated as functions of time after occurrence of the initial fire. In most cases exists a maximum of p_f indicating the most critical situation during a fire. The decrease of p_f after the maximum results either from the cooling phase of the fire or from the effect of fire suppression; the closure of the air ventilation has no influence because of the unreliable actuation. Beside the frequency p_f also the time-dependent squared weighting factors $ά_i^2$ (equivalent values related to the overall system) were determined. For illustration, the frequency p_f and weighting factors $ά_i^2$ from the analysis of the area of the main cooling pumps in the reactor building containment are depicted in Fig. 4. The main impact of the fire on safety systems comes from fire-induced failures of electrical equipment. Only the "regular" temperature-time-history a is of interest. The most critical situation is reached in an early stage of the fire when fire fighting by the fire suppression system is not yet manually actuated.

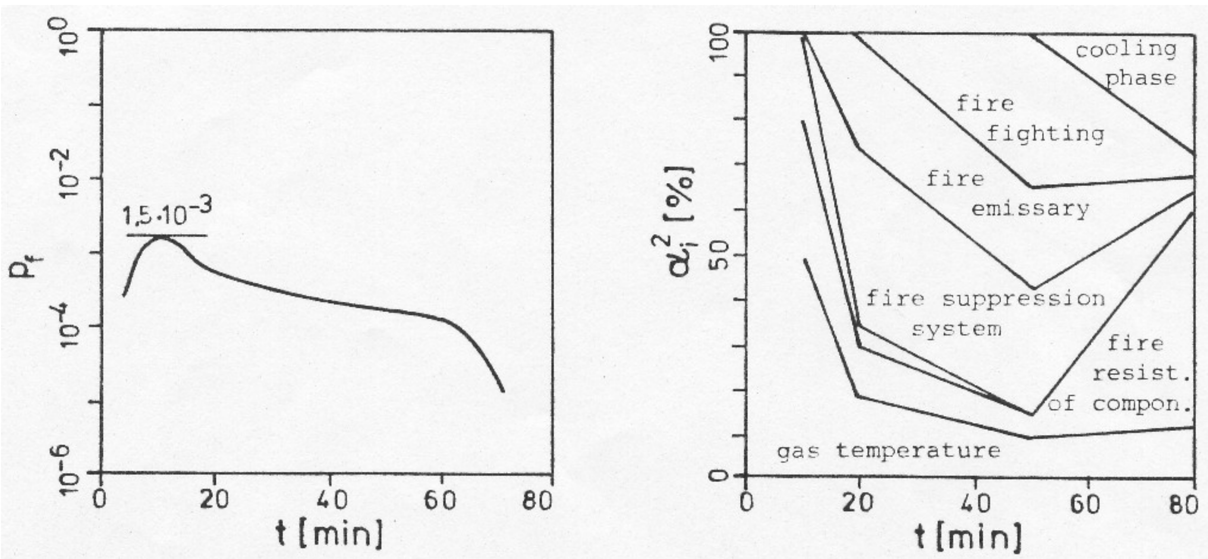

Fig. 4 Time-dependent frequency p_f and squared weighting factors $ά_i^2$ of parameters for the event "fire-induced loss of the main cooling pumps"

Important parameters at this stage are the gas temperature and the ultimate temperature of the electrical equipment in this area. About 10 min. after the occurrence of the initial fire the early fire fighting by the suppression system becomes effective and p_f is reduced. Further reductions of p_f come from the effect of the late fire fighting and the beginning of the cooling phase of the fire. As the failure of the electrical equipment of all main cooling pumps is to be expected at an early time, the only way to reduce the failure frequency p_f is to actuate immediately the fire suppression system, either manually from the control room after checking the situation by TV monitors or automatically by fire detectors. Such a modification would also reduce the risk to plant personnel and limit the damage due to spreading corrosive smoke.

CONCLUSIONS

A probabilistic method for the quantitative evaluation of fire hazards in nuclear power installations has been developed. It is based on fire event sequences which depend on success or failure of different active or passive fire protection measures. Single failures of these measures and of safety systems endangered by a fire are dependent events due to the common influence of the fire effects. With the help of a first-order reliability method the dependences can be modelled and properly taken into account in the event tree analysis. Beside frequencies of undesired consequences of event sequences, relative weights of event sequences, fire protection measures and parameters influencing the measures are determined. Based on such information weak points in fire safety concepts can easily be identified and optimal combinations of fire protection measures for a required fire safety level can be recommended.