Risk Concepts in Fire Safety Design

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Summary

Fire safety design can basically be performed by two methods, namely the simplified design method and a method based on an engineering solution. This paper summarises various risk methods and their application in the field of fire safety design. Methods covered are the reliability index β method, risk index methods and both standard as well as extended quantitative risk analysis methods. Full reports could be downloaded from http://www.brand.lth.se/english.

Keywords: .risk analysis, fire safety design, reliability, index, quantitative assessment

1. Introduction

Traditionally, fire safety design has been highly reliant on prescriptive rules in building codes. This is particularly the case for occupant safety in the event of fire. Better understanding of the fire phenomena in combination with education at university level and requests for flexibility in building design, cost-effectiveness and implementation of new technology, has led to development of performance-based building codes in several countries during the last two decades. In a performance-based code, the design objectives are defined with emphasis on what should be accomplished, and it is not stated in detail how the objectives should be achieved. There are basically two methods available to fulfill the requirements; *the simplified design method* and *design based on calculations*.

The first of these design methods is actually very similar to the 'deemed to satisfy' provisions incorporated in the former prescriptive code. The architect or designer follows simple rules or approved solutions, when the fire safety measures are designed. There are, of course, alternative solutions within the boundary of the simplified design method as was the case with the prescriptive regulations.

The alternative method, design based on calculations, uses engineering methodology 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. The keywords are now 'demonstrate' and 'verify'. Fig. 1 outlines the design process.

In Sweden most traditional approved solutions are still accepted, so it is clear that there were no intentions to introduce a higher level of fire safety in buildings when the transition from prescriptive to performance based building codes took place in 1994. When familiar traditional buildings are designed in a straightforward manner, the simplified design method is often the most cost-effective. In this case there is no need for a more complex and time-consuming design method.

In many situations, there can be conflicts of interests between fire-protection and other objectives, related to architectural design, building construction, or the business activities planned for the building. By using alternative solutions, conflicts can often be avoided. In many situations it is possible to design a building in a more cost-effective way, by using an engineering approach to fire safety design. Cost-effectiveness can mean potentially higher incomes or other increased benefits for the owner. It can also include savings of the total building and maintenance cost, related to other areas than fire protection systems, for example HVAC or structural design.

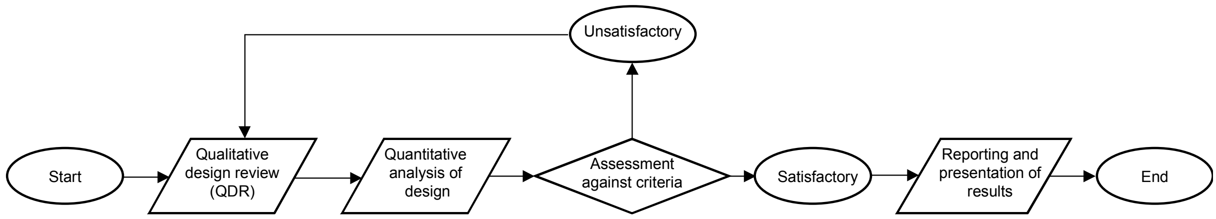

Fig. 1 The basic fire safety design process

By adopting design based on calculation it is possible for the fire protection engineer to derive an alternative solution to the simplified design. This is often performed as some kind of trade-off, since it is only necessary to change the part of the total traditional fire safety strategy that is in conflict with other objectives. There is a need to verify that the alternative design meets the performance-based safety objectives of the building code.

It is therefore natural to adopt risk analysis methods and use them on fire engineering problems. This has been an on-going process for some time in many countries and is expressed in terms of new handbooks covering the area [1].

2. Risk-Based Fire Safety Design

The most common definition of risk used in fire safety engineering (FSE) is the one adopted by the International Electrotechnical Commission [2]. Risk management can be considered as being the complete methodology that contains both qualitative and quantitative analysis methods. The IEC defines risk as a combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event. Note that the concept of risk always has two elements: the frequency or probability with which a hazardous event is expected to occur and the consequences of the hazardous event.

There are generally three types of risk-analysis methods: *qualitative, semi-quantitative* and *quantitative methods*. Qualitative methods are often used in an informal way when a well-defined trade-off is evaluated and the effect on the fire safety strategy is limited. 'Designer experience' and 'engineering judgement' are often sufficient to make minor alternations to existing accepted solutions or to rank performance of different safety measures qualitatively. The performance criterion used in the verification is relative and can be expressed as 'as safe as' or 'not worse than'.

Semi-quantitative methods are until now not frequently used in the design process of buildings. In industrial risk management methods like balanced scorecard and index methods have been widely used to rank and prioritise different preventive safety measures. In Sweden, similar methods are developed for healthcare facilities as a tool to use for fire service inspection [3]. This type of method has so far not been used in fire safety design since trade-off between different safety objectives in the building code has so far only been implicitly allowed. 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, 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 QRA including several scenarios, when explicit account of uncertainties has to be taken.

2.1 Risk index methods

In many situations when the fire safety must be evaluated there is no time or money available to perform a detailed quantitative risk analysis. Therefore there exist a need for simple semi-quantitative risk tools. During the years different approaches have been taken in order to develop ranking schemes like the Gretener system and different NFPA methods. The Gretener system is based on Swiss statistics from insurance companies and may primarily be used for industrial applications. NFPA schemes are available for different types of buildings but they are basically applicable for US building tradition.

In Sweden a ranking scheme has been developed for hospitals. It follows methods used in Great Britain and is based on Multi Attribute Decision-Making (MADM). In MADM decision weights are chosen according to the decision-maker's preferences and the weights are combined with parameter grades, which can be used to calculate a risk value. Different calculational procedures are available for this but the Simple Additive Weighting (SAW) method is mostly used.

The methodology behind the various risk index methods is quite the same. The engineer has to structure his problem in hierarchal order. The hierarchy consists of different levels, e.g. policy, aim, tactics and components. In FSE the policy could be sufficient fire safety with the aim providing protection to the people and the property. The tactics to fulfil the objectives could be prevent ignition, limit the spread of fire and combustion products, safe evacuation and to extinguish the fire. Important components to execute the tactics are then identified. These components are e.g. number of exits, sprinkler systems, and fire separation. A more detailed exemplification of the risk index method could be found in [4]. Tab 1. below illustrates the hierarchical structure of the method.

Tab. 1 Example of hierarchy used in a risk index method

Level 1 (policy)	Level 2 (objectives)	Level 3 (tactics)	Level 4 (components)
Sufficient fire safety	Protect people	Prevent ignition	People
	Protect property	Limit the spread of fire and smoke	Sprinkler systems
		Safe evacuation	Number of exits
		Extinguish the fire	Smoke ventilation
			Fire detection
			Fire separation
			Building materials

2.2 Reliability index β method

The method by which the design values are derived is based on the FOSM analytical reliability index β_{HL} method. This index can be used to estimate the probability that the system will fail, in this case equivalent to the situation where at least one person is unable to escape safely. The design problem can be formulated in terms of a limit state function, $t_{critical} - t_{evacuation} = 0$. Now the objective is to find a solution that satisfies the condition $P(G < 0) < p_{target}$ for a class of buildings and not just one single well specified building.

The procedure is to specify the target reliability index β_{HL} and the variables, both random and constants, and to vary the design parameter until the target reliability index β_{HL} is obtained. The design parameter may, for example, be the escape door width, which is the parameter the designer wants as the result using the deterministic design equation using the values in the worst probable failure point according to the FOSM method.

In [5] the procedure of deriving the design values and the corresponding partial coefficients illustrated. An example of application presented in [6], where the required escape door width is calculated. The use of the reliability index β method provides the engineer with a powerful simple risk-based design alternative. Instead of using the simplified design method he could use a risk-based one without adding any complexity to the problem. All the engineer has to do is to specify the room height and the floor area. Fig. 2 shows a typical design equation.

$$W = 0.385 \cdot A \cdot \left(\frac{1}{7.51 \cdot H^{0.27} \cdot A^{0.48} - 56.74 \cdot H^{0.34} - 77.53 - 0.025 \cdot A} \right)$$

Fig. 2 Design equation for the required escape door width, W

2.3 Quantitative Risk Analysis

The quantitative risk analysis (QRA) is focused on the combined effect of frequency and consequences of possible accidents. The frequency and consequences are formally combined in the QRA. 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. An example of an event tree is presented in Fig. 3.

2.3.1 Standard QRA

In fire safety engineering the standard QRA is used, for example, to compare different design solutions. The standard QRA is based on a high number of deterministic scenario outcome estimates, but the method is still considered probabilistic. When a large number of scenarios are considered, each with its individual probability, this will lead to a probabilistic measure of the risk.

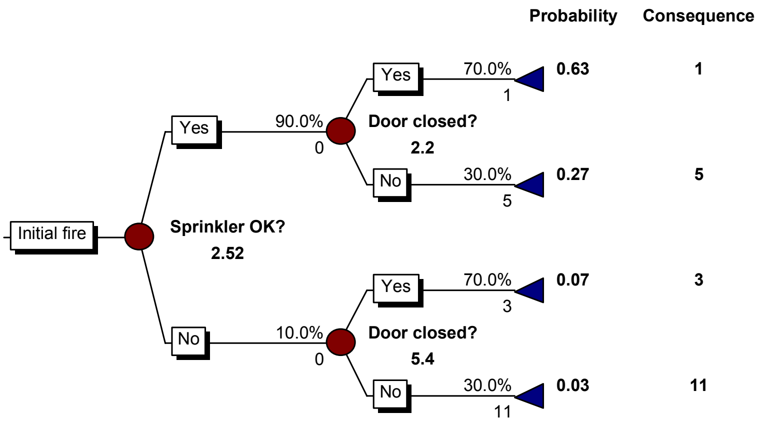

Fig. 3 An event tree for a simple fire risk analysis

The FN curve can, therefore, be seen as the empirical complementary cumulative distribution function (CCDF) for the whole event tree. The curve can also be used to compare different design solutions or to determine whether or not the design complies with tolerable risk levels.

2.3.2 Extended QRA

In a standard QRA the result can be a single FN-curve or some average societal risk. But there is no information regarding the certainty of the FN-curve. To be able to make a rationale decision one also need to know about the probable uncertainty of this result. There is a method available for this, extended QRA, which combines traditional uncertainty analysis, and standard QRA. By defining the parameters describing the standard QRA system with information regarding the uncertainty the extended QRA can be obtained by running a Monte Carlo simulation of the standard QRA system. The process can therefore be seen as a standard QRA performed a large number of times. The process of the extended QRA is very similar to that for the standard QRA [7]. Fig. 4 shows the process schematically.

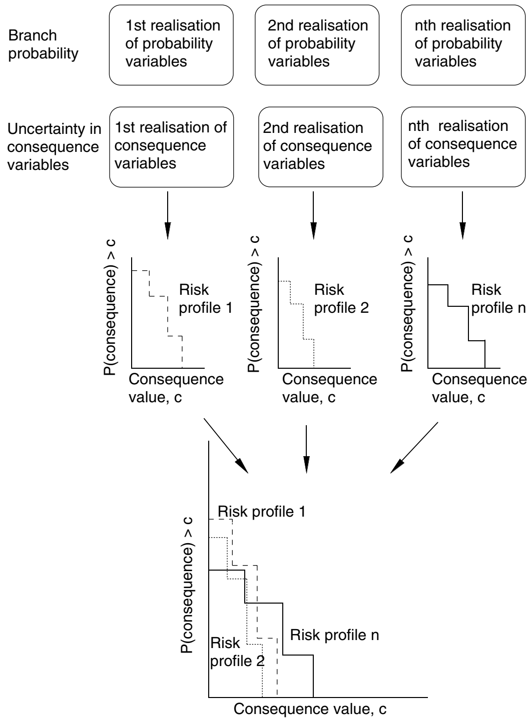

Fig. 4 Uncertainty analysis of a QRA

The societal risk resulting from the extended QRA is expressed in terms of a family of risk profiles such as those shown in Fig. 5. The family of risk profiles shows how the uncertainty in the variables affects the risk result, i.e. there is no unique risk profile but a range within which the most likely risk profile can be found. The figure shows the result using the same example as before with the sprinkler system installed. Many of the variables are now subject to uncertainty and described by distributions instead of single values. Examples of random variables are response time, fire growth rate and movement times.

It is clear that the information resulting from the extended QRA is very extensive. For each value on the horizontal axis there is no unique probability value but a probability distribution of the risk probability. Therefore, alternative presentation methods may have to be used in order to be able to interpret the information. A better method is to present the societal risk profiles in terms of the median or mean risk profile and to complement these with relevant confidence bounds. These confidence bounds show the variation in risk or more explicit, the variation in the probability for a certain consequence. The confidence interval can, for example, be the 80% interval.

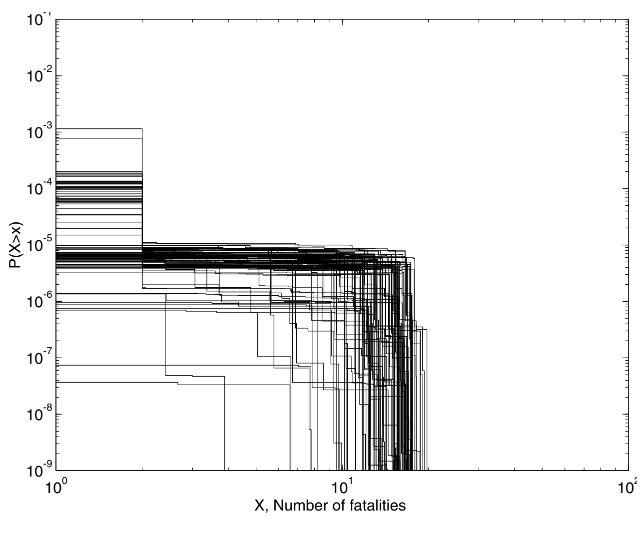

Fig. 5 Family of risk profiles from an extended QRA

3. Discussion

It is not true to say that using risk analysis in fire safety design will be the solution to all problems. Instead new ones are introduced and some of them are considered in research projects around the world, while others are still waiting to be addressed.

Depending on the complexity or magnitude of a trade-off, different methods are necessary to verify that the safety objectives are fulfilled. Today many consultants do not distinguish between minor and complex trade-offs. The current form of documentation is thereby insufficient to serve as a base for safety verification. Some trade-offs ought to require a QRA to be able to verify that the safety objectives are met, while others are simple and can be dealt with using simple calculations. How can the scope of the analysis be identified so that the proper verification can be done, i.e. what level of analysis is required in different situations? Today the consultant makes the selection arbitrarily. How should quality assurance be included in FSE? Today fire consultants can show that almost any solution is safe, by adopting an insufficient level of verification. Is it necessary to have peer-reviews of all solutions performed with design based on calculations? The approaches adopted by the local authorities having jurisdiction in Sweden vary a great deal.

In the area of FSE, there are no generally agreed quantitative levels of acceptable risk available. That makes it difficult to specify design criteria when the QRA method is used. If the scope of the performance-based design is some kind of trade-offs from a simplified solution, one way to approach the problem is to carry out a comparative QRA. The design criterion in such an analysis is that the risk level in the alternative design does not exceed the risk level in the simplified design. Drawbacks with this approach are that the simplified design must be made and analysed, which requires time and resources.

Another problem is that the limitations on simplified design are not clearly stated. It has been noticed that for many modern typ1es of building the simplified method is clearly inappropriate. For such buildings it is difficult to obtain design criteria and it is difficult to define for what types of buildings that the simplified design methods are inappropriate. It is also evident that not all aspects of acceptable risk can be incorporated into a quantitative risk measure.

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4. References

[1] Jönsson R. & Lundin J., “The Swedish Case Study; Different Design Methods Applied on a High Rise Building”. *Proc. 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods*, The Society of Fire Protection Engineers, Bethesda, 1998.

[2] International Electrotechnical Commission (IEC): *International Standard 60300-3-9, Dependability management – Part 3: Application guide – Section 9: Risk analysis of technological systems*, Geneva, 1995.

[3] Frantzich H., *Brandskyddsvärdering av vårdavdelningar - Ett riskanalysverktyg.* Dept of Fire Safety Eng. Lund University, Lund, 2000. *(In Swedish).*

[4] Budnick, E., McKenna, L.A, Watts, J.M., “Quantifying Fire Risk for Telecommunications Network Integrity”, *Proc. 5th Int. Symp. on Fire Safety Science,* Melbourne, 1997.

[5] Magnusson, S.E, Frantzich, H., Karlsson, B., Särdqvist, S., ”Determination of Safety Factors in Design Based on Performance”, *Proc. 4th Int. Symp. on Fire Safety Science*, pp 937-948, Gaithersburg, 1994.

[6] Olsson, F., Frantzich, H., “A Simple Risk-Based Design Method”, *Proc. 3rd Int. Conf. On Performance-Based Codes and Fire Safety Design Methods*, The Society of Fire Protection Engineers Lund, 2000.

[7] Frantzich, H., “Risk Analysis and Fire Safety Engineering”, *Fire Safety Journal,* 31 (1998), pp 313-329.