Fire Safety Design when Normal Limits Don't Apply

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INTRODUCTION

Swedish building regulations are performance based since 1994. The regulations contain both mandatory provisions and general recommendations. The performance requirements are covered in the mandatory provisions and the general recommendations give the engineer proposals on how the requirements could be meet. Historically, building regulations have been developed by some kind of trial and error approach. Building facades of wood were forbidden as a consequence of the large town fires in the 18^{th} century, etc. With this approach the regulations are formed by the national building traditions. In modern architectural design traditional buildings are rather uncommon. High-rise multi-occupancy buildings, enormous shopping malls and entertainment centres are examples of non-traditional buildings. In order to comply with the building codes the engineer could chose either a prescriptive design method or an analytical method. When the prescriptive method is used, deemed to satisfy solutions must be applied without any trade-offs. Analytical methods do, however, consider the overall fire safety and make it possible to do certain trade-offs. Design freedoms are allowed and the fire protection could be optimised.

BEYOND NORMAL LIMITS

The buildings described in the introduction require performance-based fire safety engineering approach rather that the use of prescriptive methods. A design based on engineering methods need to be verified. Using various analytical methods on fire development and evacuation usually carries out this verification. Finally, an assessment against criteria is performed. It is quite common that the acceptance criteria to be used in evaluation are based on the safety level achieved if the general recommendations would have been used. A design is considered acceptable if the safety level is equal to or higher than the acceptance criteria. This approach is usually named a comparative analysis. However, this comparative approach must be questioned. How is it possible to evaluate a design of a non-traditional building towards deemed to satisfy solutions developed by the present building traditions? The main argument to use analytical methods is that prescriptive solutions are not applicable. It may therefore seem quite contradictive to perform a comparative analysis towards the non-applicable traditional solution. It is necessary that the fire safety community develop a new basis for design evaluation. As absolute fire risk criteria are absent a more qualitative approach must be applied.

A QUALITATIVE APPROACH

Methods for developing acceptable risk have discussed in the community in last few years. In doing so a number of fundamental risk evaluation principles has been withdrawn. Risk can be evaluated and risk criteria established using four different principles (Davidsson et al, 1997).

- *The principle of reasonableness* says that an activity should not involve risks that by reasonable means could be avoided. Risk that by technically and economically reasonable means could be eliminated or reduced is always taken care of, irrespective of the actual risk level.
- *The principle of proportionality* means that the total risk that an activity involves should not be disproportionate to its benefits.
- By using *the principle of distribution*, risks should be legitimately distributed in society, related to the benefits of the activity involved. Single persons should not be exposed to disproportionate risk in comparison with the advantage that the activity affords them.
- *The principle of avoiding catastrophes* says that it is better that risks are realised in accidents with a lower number of fatalities. When discussing risk reduction, terms such as *ALARP (*As Low As Reasonably Practicable) and *ALARA* (As Low As Reasonable Achievable) are frequently used.

It is necessary to interpret these fundamental principles towards the field of fire safety design. The principle of reasonableness is taken care of by following the performance requirements in the regulations. The principle of proportionality says that higher fire risks are accepted in a certain building if there are certain financial benefits from it. The industry owner has a much greater responsibility to by him self, find a reasonable fire safety level. The principle of distribution related to requirements on fire compartmentation, separation between buildings, etc. Those who cannot control the outbreak of a certain fire should neither be affected by it.

The most suitable engineering methods for verification are those based on risk analysis. Such a method is the quantitative risk analysis method developed by Lund University (Frantzich, 1998). This method uses event tree technique and provides the designer with detailed information on the strengths and weaknesses of the proposed fire safety design. The method makes it possible to deal with variability and uncertainty related to input and models. By combining information on fire development and the evacuation process for each scenario with probability calculations, a number of risk measures could be derived. These risk measures are e.g. individual risk, average risk, risk adversity and maximal consequence. The qualitative evaluation criteria must therefore be compatible with these risk measures.

One of the most fundamental requirements in the regulations is that people's safety should be assured in the event of fire. The proposed fire safety design will therefore have it basis from the point were a fire has be initiated and allowed to develop. The following evaluation criteria are proposed.

- When a fire breaks out and all fire safety measures are operating no one is supposed to be exposed to untenable conditions. The individual risk has to be lower than 1.
- The number of safety barriers that has to fail before someone gets harmed will be used when different design alternatives are evaluated.
- The average risk should be in line with fire statistics.
- The maximal consequence must be related to the principle of avoiding catastrophes.

As input data is represented by its statistical distribution instead of best guess point estimates, the result will be presented by a probability distribution function. It is proposed that the 95th percentile of this distribution will be used when the result is evaluated. By using the 95th percentile the engineer is certain that the risk will only be worse in 5 of 100 occasions.

MODELLING FIRE RISKS

As stated in a previous section a qualitative approach requires an evaluation towards a number of these measures. The individual risk is of great interest as it describes how often one could expect a fire with unwanted consequences. The average risk is used in other fields of engineer, sometimes named potential loss of life (PPL) or average rate of death (ROD). The average risk is the weighted sum of the risk for all scenarios and describes what outcome that could be expected over the lifetime of the building. The full societal risk is commonly illustrated in a FN-diagram. In such a diagram it is possible to see the relationship between frequent fires with minor consequences and less frequent fires with catastrophic outcomes. The maximum consequence is the expected consequence when there is a failure on many of the active or passive fire safety measures in the building.

Traditional risk analyses use point estimates to present the risk. There are mainly two problems associated with this approach. First, it is highly desirable for decision-makers to be aware of the full range of possible risks in order to make balanced decisions. Second, point risk estimates frequently are very conservative as a result of the accumulation of the effects of various conservative assumptions made at intermediate steps in the analysis (Magnusson, 1997). The consideration and treatment of uncertainties in risk analysis adds considerably to the credibility of the results, which in this case is a model requirement. One approach to treat uncertainties is to employ Monte Carlo or Latin Hypercube sampling techniques. Frantzich (1998) introduced the extended QRA, which was adopted on a Swedish case study by Andersson et al (2000).

Both the standard QRA and the extended QRA has its basis 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 1 shows an example of a simple event tree for a fire. The risk of 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. The purpose with an event tree is to consider both successful and unsuccessful operation of the fire safety measures in the building.

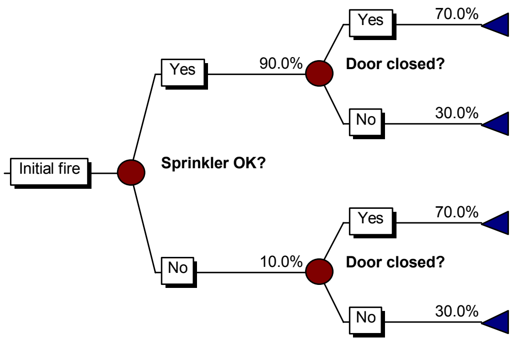

Figure 1 Example of part of a simple event tree.

What differs standard QRA from extended QRA is the use of probability distributions for the input data. Standard risk analysis software makes it possible to calculate the probabilities and consequences for each scenario by the use of thousands of iterations. The standard QRA is represented by one single iteration with design values, results in one FN-curve. A family of FN-curves represents the extended QRA. One curve for each iteration. The difference between the outcome from a standard QRA and from the extended QRA is shown in Figure 2.

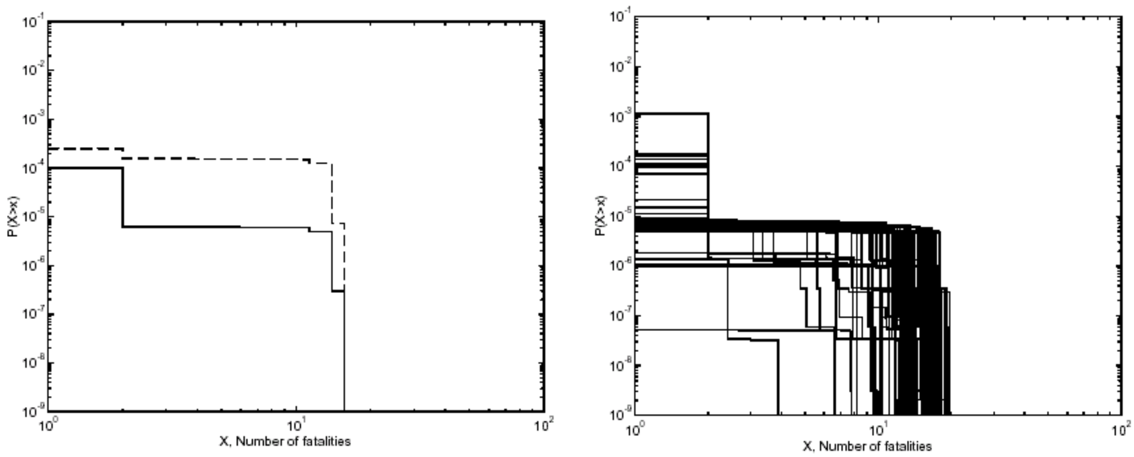

Figure 2 **FN-curves for the standard QRA (two alternatives) to the left and a family of FN-curves for the extended QRA (one alternative) to the right (Frantzich, 1998).**

Performing thousands of iterations is not a big issue with the power of today's computers. But comparing design alternatives when extended QRA is used requires more attention. If the full societal risk (FN-curves) should be derived this is quite a time consuming process. It is necessary to analyse the family of FN-curves by statistical means and deriving relevant percentiles (10^{th}, 50^{th} and 90^{th}). There is however a shortcut to evaluate design alternatives. After a simulation has been carried out there are a few measures that could be derived directly with very little effort. These measures are the individual risk, the average risk and the maximum consequence. By evaluating these measures towards the established criteria it is possible to rank and compare the proposed design alternatives. Risk modelling is basically a technique where a lot of information is structured in a logical way. Combining risk analysis techniques with traditional fire safety engineering performs fire risk modelling. Quantifying fire development and smoke spread and comparing this information with evacuation calculations carry out analytical fire safety engineering for life safety. For each scenario the safety margin as described below is assessed.

$$M = t_{critical} - t_{detection} - t_{reaction} - t_{movement}, \quad IF \left\{ \frac{M < 0, unsafe}{M \geq 0, safe} \right\}$$

When the safety margin has a negative value there will be people left in the building exposed to the code-defined untenable conditions. This safety margin can easily be converted to a suitable consequence measure, i.e. number of people unable to escape safely. In the standard QRA commonly used software models on fire development and evacuation calculations can be used one at the time. But, for the extended QRA such models need to be directly expressed to the risk calculation algorithm. A suitable way of linking this information is to use response surfaces derived from the appropriate software. More information on response surfaces is found in e.g. Olsson & Frantzich (2000).

REAL-LIFE EXPERIENCE

The qualitative evaluation criteria described above have been used in a real-life situation. At the qualitative design review of a new university building "Orkanen" in Malmö, Sweden it was decided that analytical methods had to be used for design and that a comparative analysis was not appropriate.

Building and analysis overview
The building which is the new university school of education, consists of five floors and has a total floor area of 40 000 m^2. It houses app. 3000 people with the university library on the top floor. Each floor is divided into six zones with very open and flexible design. The total project sum is 70 million USD. The main challenges for the fire safety design are requirements and design of load-bearing structures, the design of detection and extinguishing systems, travel distance to and the number of exits as well as the design of facades.

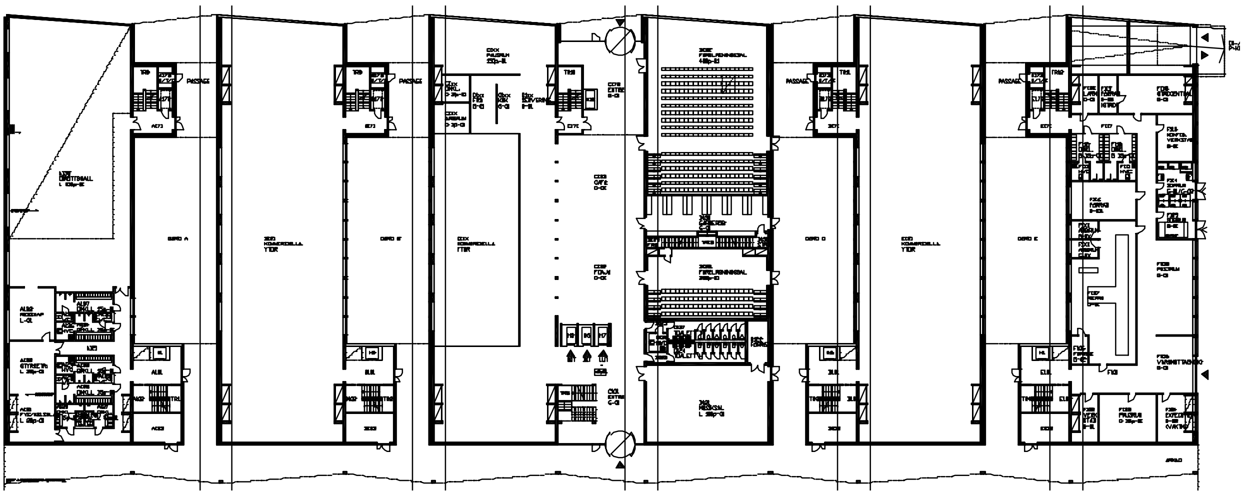

Figure 3 Plan view of "Orkanen". The university building has a length of 150 m and a width of 60 m. It has five floors and houses 3000 people.

The overall fire safety strategy of the building uses fire compartments and fire zones. One fire zone could consist of many fire compartments. The likelihood of spread of fire and fire gases should be considerably lower between fire zones than between fire compartments. Considering the size of the building it is necessary to divide it into smaller parts when analysing fire safety. The division will be based on the division into fire zones. In this paper the analysis for one of the fire zones is described. This fire zone has a floor of area app. 1000 m^2 with a very open and flexible layout.

Inputs
The fire development is assessed by response surfaces from the FAST software (Peacock et al, 1997). The evacuation process is calculated by the use of a simple hand calculation method described in Olsson & Frantzich (2000). The room height is 3.4 m and the standard door width is 1.2 m. The fire growth rate is considered to be lognormal distributed with a mean value of 0.04 kW/s^2 (fast growing fire) and a variation coefficient of 25%. The number of people in the fire zone is assessed to 200.

Three different fire safety design alternatives are proposed. The first is based on the general recommendations in the Swedish building code (BBR, 1999) and consists of three exits and a manually activated alarm bell. The second alternative has one exit less than the first and an automatic fire alarm connected to a spoken escape alarm. The third alternative consists of a fully automatic sprinkler system in addition to the safety measure of the second solution. Untenable conditions are defined in the building code. In this analysis a smoke layer height of 2 m above the floor is considered untenable. Depending on the chosen design alternative the event tree consists of all or some of the following events.

- Does the fire alarm operate as intended?
- Is the alarm bell or the spoken escape alarm working?
- Will the fire be extinguished or at least controlled by the sprinkler system?
- Will all emergency exits be available?

The answer to the questions above could either be yes or no. The probability of successful operation of fire safety measures could be found in a number of literature sources. The BSI (1997) has published some figures. Sprinkler system and fire alarm system are both considered having a reliability of 90%. The escape alarm is assessed with 85 % reliability. The fire could also block emergency exits. Using the area approach outlined by Magnusson et al (1995). This approach results in a reliability of all exits of app. 95%.

Analysis of fire development and escape

The critical time for escape needs to be calculated. This time is depending on the fire growth rate, the floor area and the ceiling height. The response surface from FAST is given below.

$$t_{critical} = 3.07\alpha^{-0.29}h^{0.27}A^{0.48} \qquad \text{[s]}$$

The equation is adopted from Olsson & Frantzich (2000) and is valid for a fire growth rate (α) of 0.003-0.19 kW/s^2, a ceiling height (h) of 3-6 m and a floor area (A) of 600-1500 m^2. In case of a sprinkler operating it is considered that untenable conditions will not occur if they have not occurred when the sprinkler is activated. The detection time is dependant on the fire alarm. Equations for the detection time for automatic and manual detection are given below.

$$t_{detection|alarm} = 21.8\alpha^{-0.31}h^{0.34} \qquad \text{[s]}$$

$$t_{detection|manually} = \frac{1}{3}t_{critical} \qquad \text{[s]}$$

The equation for automatic detection is adopted from Olsson & Frantzich (2000) and is valid in the same range as the time to reach critical conditions stated above. If the alarm dos not operate, the fire will be detected with a mean value of 2 min. The reaction time is depending on the operation of the sound system. The equations below are based on Frantzich (2001).

$$t_{reaction|alarm} = Normal(60,12) \qquad \text{[s]}$$

$$t_{reaction|no\,alarm} = Normal(90,18) \qquad \text{[s]}$$

The reaction time is considered to vary depending on whether or not smoke is visible and if there is an operating sound system. The movement time is divided into two parts, one time to reach the exit and one cueing time. If the people are evenly distributed in the floor, the time to reach an exit will be considered as zero. Cueing will occur immediately when people starts to evacuate. The cueing time is a function of the number of people (N), the sum of door widths (w) and the flow rate (f). Equations and results from Frantzich (1994) are applied.

$$t_{movement} = \frac{N}{wf} \qquad \text{[s]}$$

$$f = Triangle(1.3,1.5,1.7) \qquad \text{[people/ms]}$$

Results

The first design alternative has greater robustness as there is one additional exit compared to the two other alternatives. If one of the exits is blocked, there is still two left to be used for escape. The alternative does however lack a system that effectively acts consequence reducing. The uncertainties involved result in a fire safety design where each fire that is allowed to develop will cause damage to the people. The average risk is 140 people exposed to untenable conditions.

The second alternative has increased safety compared to the first as a result of the automatic fire alarm. At 1 of 4 developing fires there will be damage to the people. The average risk is 40 people exposed per fire. The maximal consequence has increased as one of the exits from the first alternative has been removed. Damage will nearly always occur when either the fire alarm or the sound system fail to operate.

The third alternative has the highest level of safety. The risk of getting wounded has been lowered to 1 of 25 developing fires. This value should be considered as very low. In average, 6 people will be exposed to untenable conditions per fire. The reduction in average risk is obvious compared to the other alternatives. Damage will only occur if the fire alarm, sound system and the sprinkler fail to operate at the same time.

Table 1 Summary of the result from the risk-based evaluation of each design alternative

Alternative	Individual risk	Average risk	Maximum consequence
1	1.00	140	160
2	0.27	40	175
3	0.04	6	175

Alternative 2 and 3 passes the first criteria on the risk to individuals. When alternative 2 is compared with alternative 3 there is one clear winner. Alternative 3 has superior values on both individual and average risk. Alternative 2 has an average risk that could be considered too high, as catastrophes should be avoided. Alternative 3 is considered to provide the best flexibility for future changes in the building layout. The robustness is high and damage will not occur to people if at least one of the proposed safety measures is operating.

CONCLUSIONS

Analyses like the one above have been performed for all zones of the building. In addition, fire safety engineering was used to verify code compliance for other performance requirements than life safety. By applying this extended quantitative risk analysis to the design problem some interesting fire safety features were verified. The open design of each section could be accepted. There should be two emergency exits from each zone. A fire alarm system with a public notification system in combination with a fast response sprinkler system has to be installed in order to allow these design features. The fact is that this design alternative was the only one that complied with the evaluation criteria and the performance requirements in the regulations. The risk analysis also found out that classrooms should have at least two exits to the corridors and certain lecture halls should have an increased number of exits.

If a deemed to satisfy solution has been applied the risk level would have been unacceptable. These general recommendations provide the following fire safety measures for this kind of public building. A sprinkler system would not have been installed. Separating distances between building sections with facades of glass would have been allowed unprotected. The distance is great enough for no measures to be undertaken, but the risk of fire spread is still obvious. There would not have been any requirements to install a fire alarm system. Extensive compartmentation, decreased flexibility of design and additional emergency exits would have been optional. The individual risk would have been 1 for the deemed to satisfy solution. This means that each time a fire is allowed to develop a number of people would have been exposed to untenable conditions. But, the most frightening fact is that the authorities, the public and the building owner would have been unaware of the situation if the deemed to satisfy solution had been adopted. This is true as there are no requirements to perform verifying analyses when the general recommendations are followed. Despite the difficulties related to risk based fire safety engineering methods one main advantage overrides them all. The understanding about the capacity of the building in the event of fire increases and a better understanding is the key to improved safety awareness.

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