Fire Safety Risk Analysis of a Hotel; How to Consider Parameter Uncertainty

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Abstract: The reliability index β First Order Second Moment (FOSM) method was used to derive a risk measure for the safety of people in a hotel, safety being expressed as the escape time margin, or the difference between the time available before untenable conditions develop and the evacuation time. These times are subject to uncertainty. The reliability index expresses the probability that the escape time margin will be negative, i.e. that failure will occur. How the reliability index is influenced by the escape alarm system and the smoke detection system employed is investigated. The risk measure is derived for a guest in the room where the fire occurs and for other guests on the same floor, only fires in this guest's room being considered.

Keywords: Risk analysis, FOSM method, fire, evacuation, reliability index, hotel

INTRODUCTION

This paper presents a method for quantifying the individual risk to a hotel guest in case of fire. The risk measure obtained allows different design solutions to be compared in terms of relative risk so as to evaluate which design alternative has the best expected outcome. If a fire occurs in a hotel, the guests are usually evacuated as quickly as possible. This is usually the strategy selected first by the management and by the fire brigade. Another alternative, however, is to have guests stay in their rooms for some time, waiting for the fire brigade to extinguish the fire, their being evacuated later if necessary, the assumption being that guests staying in their rooms tend to be safe, due to each guest room in a hotel being a separate fire compartment.

On the other hand, the development of some fires recently, in particular the fires in the MGM Grand Hotel in Las Vegas and the Hotel Caledonien in Norway, suggest that this latter alternative may not be the best solution for hotel guests (Bryan, 1983; DBE, 1987). In both cases, smoke entered the rooms in which people were staying, in the Norwegian fire almost all fatalities occurring among people in their rooms.

Accordingly, the strategy considered in this report involves the guests' leaving their rooms as soon as they have been alerted to the danger or responded to the fire-induced cues, its being assumed that guests endeavour to escape through the corridor, this leading them to a safe location. The risk measure is derived for guests at two separate locations, the room where fire occurs and the corridor. It is used then to compare different design solutions and to indicate the safest alternative. Staircases at both ends of the corridor represent the safe location towards which the guests are heading. The rooms are assumed to be located on both sides of the corridor. Two different corridor lengths are used in the calculations. Such a standardised floor configuration is used to reduce the number of variables that are subject to uncertainty.

The dimensions chosen for the floor are representative for hotels in Sweden designed according to traditional methods.

THE BUILDING

The risk measure is derived for the occupants on one floor in a multi-level hotel. It is assumed that the guests can evacuate without any assistance from other guests or members of the hotel staff. The actions of the staff are restricted to starting the escape alarm when the fire has been detected, either by an automatic fire alarm or manually. The escape alarm is set off by a staff member after investigating the cause of the alarm. When the escape alarm sounds, the guests respond to the alarm signal and after a some period of time begin to evacuate. It is assumed that the hotel is manned around the clock and that the staff members are familiar with the procedures in case of fire.

Each guest room has a floor area of 6.5 m^2 and a height to the ceiling of 2.4 m. It also has a window 0.9·0.9 m^2 to the outside and a door 1.0·2.0 m^2 leading to the corridor. Each room is a separate fire compartment with a resistance time of one hour to the next room and to the corridor. The door to the corridor has a 30-minute rating. It is equipped with a closing device which closes the door after passage.

Two types of floor configurations are used, involving corridor lengths of 30 m or 60 m, respectively. The corridors are 3 m wide and 2.5 m high. The number of guest rooms, 12 rooms and 24, respectively, is determined by the length of the corridor. The longer corridor length corresponds to the maximum length allowed by the Swedish Building Code (BBR94, 1994), which states that the maximum distance allowed in the escape route to a stair or to the outside is 30 m. It is assumed that there is one guest in each room and that no queuing occurs at the staircases leading to the ground floor.

The walls and ceiling are covered by gypsum sheets applied on noncombustible material. The floor is constructed of concrete. The gypsum sheets are of the highest performance class.

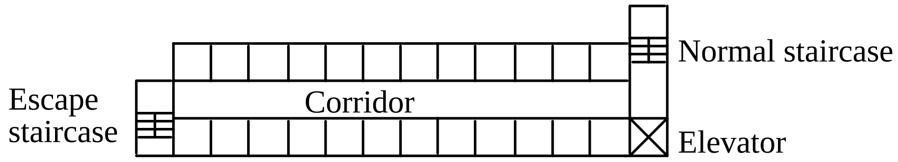

Figure 1. Principal layout of the 60 m floor.

Staircases leading to the ground floor are assumed to be located at both ends of the corridor. The doors leading to the staircases are initially closed, but open during evacuation, letting smoke and people out to the staircase. To simulate this, these doors, having an area of 0.1·2.0 m (W·H), are assumed to be kept open during the entire simulation. This is an engineering assumption which makes the fire calculations smoother. The staircases are assumed to be a place of safety.

THE UNCERTAINTY OF VARIABLES

Since the only question of risk considered in this paper involves the comparison of different design alternatives, the initial fire occurrence rate can be disregarded. If a full Quantitative Risk Analysis (QRA) (Frantzich, 1998) is aimed at, this simplification cannot be made. Risk exists due to the fact that some variables, the basic variables, are subject to uncertainty. This means that, because of this randomness, situations may occur in which not all the guests can be safely evacuated. The fire that threatens can develop rapidly, at the same time as evacuation may for by some reason be delayed, leading to unsuccessful evacuation. The probability of the latter occurring can be derived, the risk obtained being a quantitative measure of the size of this probability. The uncertainty variable can be described by a probability density function, i.e. a statistical distribution, indicating the values the variable can be take and how often these can be expected to occur. The current value of a basic variable is selected at random from this distribution, the basic variable thus being a random variable. The distribution can be defined by the parameters of mean and standard deviation, which need to be selected for the risk calculations.

The parameters describing the distributions of the basic variables are chosen according to

- experimental data and statistics
- judgements made by experts

For most variables, little systematic information is available that can provide guidance on how to choose parameters for the distributions. Experiments can lead to the choice of some parameters but no systematic basis for the choice of a specific value as the mean or standard deviation has been established. Since the overall experimental database is very large and not easily accessible, there is no easy way to obtain the parameters from that source. It is necessary, therefore, to estimate the parameters judgementally, selecting a distribution type on basis of degree of belief (Haimes et al., 1994). Such a procedure for estimating the parameters, based on the use of expert opinion, is quite common in other engineering fields in which experimental data is lacking such as in the chemical process industry (CPQRA, 1989).

DEFINITION OF RISK

Before introducing different occupant risk analysis methods, it is necessary to define what is meant by risk. The risk associated with fire in a building takes into account the likelihood of fires and their potential consequences, e.g. the possible numbers of deaths. Hence it is possible to define risk as a function of hazard, probability and consequences:

$$\text{Risk} = f\,(\text{hazard, probability, consequences})$$

When calculating the risk associated with a particular hazard it is more common to write

$$\text{Risk} = \Sigma\ (\text{probability , consequence}), \text{ for all consequences.}$$

The fire risk in a building can be expressed either in monetary units/year if the fire loss consequence on average is X units and the probability of a fire is Y % per year, or in number of deaths per year. Yet risk is not always simply the product of multiplying of two quantities, i.e. a numerical value. There is a distinction between calculated risk and perceived risk. The latter is important defining acceptable risk. An important aspect of risk is the degree of voluntariness with which the decision to expose oneself to it is taken. The person making such a decision weighs the risk of the activity against its advantages. A person may engage in the activity in question voluntarily and thus very likely be ready to accept a higher degree of risk, for example in climbing mountains. The present report focuses on use of a quantitative measure of risk. Also, where the distinction can be made between the categories of individual risk and societal risk, the paper concerns only a measure of the former type of risk. Individual risk involves the probability that a person will be affected by an unwanted consequence or, when several persons are considered, that the accident or event will result in one or more casualties. However, the only probability that will be derived is the one arising from the fact that variables are subject to uncertainty. This means that the subscenario probability is not part of the risk measure. This should be considered when comparing the risks here with other risks in society.

QUANTIFYING THE HAZARD

Safety in the present context can be described in terms of the margin of escape time. When a fire occurs in or in the vicinity of a room, only a certain time is available before remaining in the room becomes untenable for human beings. Comparing the time available for escape with the time needed for it, the escape time margin can be calculated as

$$G = t_a - t_e \qquad [1]$$

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

This equation is referred to as 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 as 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 subject 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 in a corresponding distribution of the escape margin.

The complete limit state function for the risk calculations here is

$$G = S\ ,\ U_s - D - t_{Inv} - R_{Fire} - R_{Neighb} - E - t_{Button} \qquad [2]$$

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_{MRoom}, $t_{MCorr60}$, $t_{MCorr30}$)
t_{Button} = time for a guest to move to an alarm button

Not all the variables were used at the same time, they were their being assigned the value of 0 for some subscenarios. The variables S and calculated detection time are both functions of the fire growth rate α. The risk measure was calculated for two locations in the hotel, in the room in which there was fire and in the corridor. The corridor was chosen since the guests in the neighbouring rooms would have to pass through the corridor on their way to a safe location.

THE RISK ANALYSIS METHOD

The life safety here is expressed by the First Order Second Moment (FOSM) reliability index β (Thoft-Christensen and Baker, 1982), the version of it employed in the present analysis being one first presented by Hasofer and Lind in 1974. It has been applied previously to fire safety problems by, for example, Magnusson et al. (1994) and Magnusson et al. (1995). This measure represents a value for safety which is comparable between different solutions. It was calculated both for occupants of the room where the fire originated and for occupants of other rooms trying to escape through the corridor. For the guests trying to escape through the corridor, two indices are presented, one for each corridor length.

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

$$p_{u,i} \cong 1 - \Phi(\beta) \quad [3]$$

The symbol Φ denotes the standardised normal distribution function and $p_{u,i}$ the probability of failure in subscenario 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. In this paper the Rackwitz algorithm is employed. That method has been modified slightly in order to be able to consider non-normal distributions as well. A description of the Rackwitz algorithm is found in Ang et al. (1984). The reliability calculations were performed using the computer program STRUREL (1995).

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 subscenarios 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 subscenario at the time.

EVENT TREE DESCRIPTION

The calculations of evacuation safety were structured by the event tree technique, which is a way of logically structuring the scenario and showing graphically the different subscenarios or event tree outcomes. The event tree organises the events that can occur, such as the detection system failing or the door to a guest room being open. There is a certain probability associated with each possible event. Combining these probabilities, one can calculate the probability of a given scenario. The event tree for the calculations here is presented in Figure 2.

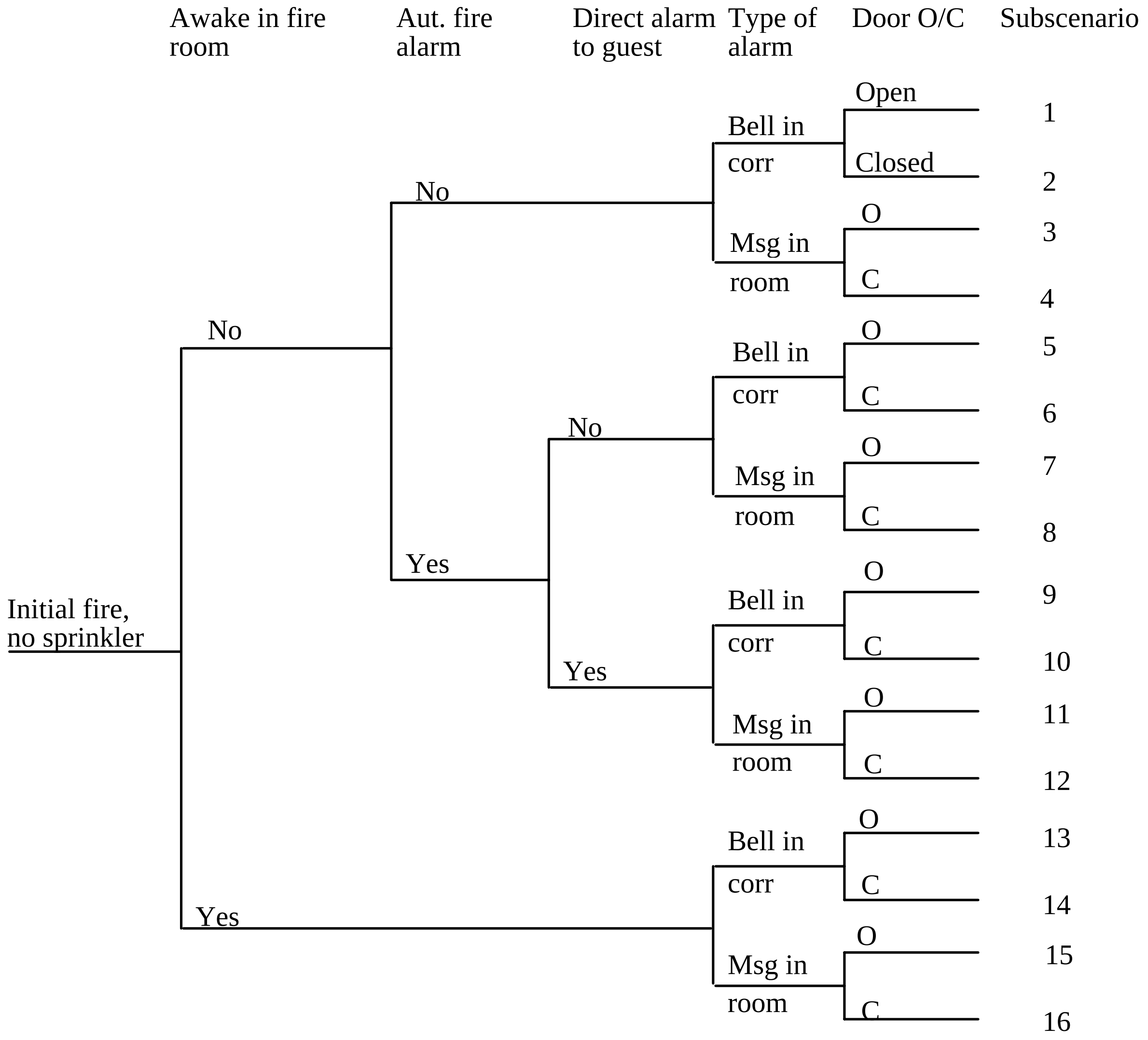

Figure 2. General event tree describing the basic subscenarios.

PRESENTING INDIVIDUAL RISK

Many different methods for presenting the quantitative results a risk analysis are available. The choice of methods depends in part on the sort of information to be presented. Individual risk to humans from a hazard due to a chemical plant could be presented, for example, in the form of risk contours plotted on a map to show the dependence of individual risk on the distance from the point of release of the chemical in question the risk decreasing with distance from this point. The risk can also differ with direction from the source, due to variability in the wind direction.

To be able to include information about the likelihoods of the different subscenarios, a new method of presentation is employed. The β-values, representing the consequences of the subscenarios, are plotted against the likelihood of the corresponding subscenarios. This means that a specific design, i.e. a particular design for the safety strategy of the hotel, is studied here each time. This is a consequence of the fact that a hotel would not, for example, have both types of escape alarms installed. A typical design could be a 24 room corridor with an escape-alarm bell located in the corridor only. Since not all subscenario outcomes are of interest, many need not be examined. Differences in the assumptions made regarding the basic variables also affect the level of the reliability index β.

Each safety design results in a curve which connects its β-value with the different outcome-probability pairs. Curves of this sort can be used to compare different design solutions, see Figure 4. One should note that the x-axis in the figure, indicating the values of β, is highly nonlinear in terms of the consequence level. The probability of failure, for example, is not 50% less if the value of β is increased from 1 to 1.5, according to Eq. [3] the corresponding probabilities being 15.8 % and 6.7 % for $\beta = 1$ and $\beta = 1.5$, respectively. A safe design should be located in the lower left corner of the diagram.

The different β–value and subscenario probability pairs are sorted in terms of decreasing β-values, i.e. of increasing hazard. The outcome probabilities used in the diagram represent the complementary cumulative probabilities, the highest β-value having a probability of occurrence of $1\text{-}p_{\beta 1}$. Reducing each outcome probability by the outcome probability preceding it results in a form of complementary cumulative distribution function, CCDF, which shows the risk level in a manner similar to that presented in IAEA (1989). The CCDF indicates the probability of consequences occurring that are worse than the respective value on the x-axis.

CALCULATING THE CONSEQUENCES

The consequences are expressed in terms of the probability of having a negative escape time margin, using the limit state function. The values of the variables in this function need to be determined, the values employed being shown in Table 1. The subscenario probabilities can be found in the event tree, Figure 2.

The time until untenable conditions are reached is derived using the computer model CFAST (Peacock et al., 1994). The energy release rate from the fire is assumed to follow an αt^2 relationship. The location of the fire can be either in one of the guest-rooms or in an adjacent part of the building. In the latter case it is assumed that smoke enters the corridor through an elevator shafts, a staircases or some similar vertical opening. Since the calculations here are the same as for a fire located in guest room, it was not necessary to study further scenarios.

The model uncertainty in CFAST was employed using a correction factor for the available time, U_S.

The detection time depends on how the fire is detected. If it is first detected by means of the fire alarm, the detection time is calculated using the program Detact-t2 (Evans et al., 1985). If the person in the room is awake when the fire breaks out and does not succeed in extinguishing the fire, the detection time is a function of the variable t_{Det2}. For cases in which the fire is detected by someone outside the room the detection time is a function of the variable t_{Det1}.

When the fire is detected by means of the fire alarm, it is the staff who is first informed. They investigate the reason the for the alarm going off. It is assumed that the investigation time is t_{Inv}. In other cases, the staff participates in no active way in the evacuation.

When the guest in the room where there is fire becomes aware of the fire, he or she must take some action. The action sequence can depend very much on the specific individual involved. Frequent actions of guests in hotels under such circumstances are those of getting dressed, alerting roommates, or looking out through the window. In the end, the person tries to escape from the room to a place of safety. The response and behaviour time includes the time spent carrying out all the actions prior to initiating the action to escape is initiated. The behaviour time can also include actions performed during evacuation.

The response time of the guest in the room where the fire originates is expressed as the time R_{Fire}. For people in other rooms, the response time depends on the type of escape alarm. The time assumed apply to night conditions, when all the guests in the hotel are asleep. After hearing the alarm signal, a guest must first wake up and understand the need of leaving the room for a safe place. Two different types of alarm signals are investigated: flashing light in combination with an alarm tone and an ordinary alarm bell. Alarm signals which contains more information than an alarm bell, for example, result in shorter response and behaviour times, resulting in a higher safety level, (Bellamy et al., 1990). An informative verbal message or a light and sound signal in the room could be good escape alarm signals. If a combination of flashing light and sound is used, a notice should be present informing guests of the meaning the signals have and of what they are to do when they both hear and see an alarm signal. If the escape alarm is the combination of a flashing light and a tone signal in the guest's room, the time displays a lognormal distribution $\Lambda(60, 30)$ seconds. This time is denoted $R_{Neighb2}$. If only an alarm bell located in the corridor is used, the response time will be lognormally distributed $\Lambda(120, 20)$ seconds. This time is denoted $R_{Neighb1}$.

According to the building code, an escape alarm is mandatory for hotels in Sweden. In all hotels, alarm buttons are to be present on every floor, notifying the staff, for example, of a fire. In some cases, the escape alarm starts directly, at least on the floor where the button is located, when any of the alarm buttons is pushed. This is also assumed in all of the calculations. If no staff member is present in the hotel, the escape alarm is to start after less than 30 seconds if the fire is detected by an automatic fire alarm. The probability that the escape alarm will work when needed is included in the data for the automatic fire alarm. For those cases in which a direct alarm is sounded in the room where there is fire, the availability of that devise is set to 0.98.

It is assumed that the guests are representative for the average population of persons visiting hotels. This includes some persons suffering from physical disabilities, i.e. wheelchair users and the like. All guests are assumed to be capable of understanding the fire threat, even if it may take a long time in some cases. It is assumed that no mentally disabled persons are present.

The movement time is the time spent by guests in moving from their rooms to the point of safety. The guests are assumed to be safe when they have reached the staircases at the ends of the corridor. The guest in the room which is on fire is assumed to be in safety, however, as soon as being outside the room. It is assumed that no queuing problems arise when people enter the staircases. This assumption is basically valid if the number of persons escaping is fairly small, as in the present case.

It is assumed that the height of the smoke layer and of the temperature are independent of the position in the corridor of the room that is on fire. A fire in a room at the end of the corridor is thus assumed to result in the same conditions as present when the fire is in a room located in the middle of the corridor. To take variation of this sort into account, differing travel times in the corridor can be employed. If the fire starts in a room near one of the staircases, that staircase is assumed to be blocked and unable to be used. The guests then must use the other staircase, meaning in the long corridor that the guest closest to the fire must move a distance of 60 m. If the fire is located in the middle of the corridor on the other hand, both staircases can be used and the guest closest to the fire has only 30 m to move. If it is assumed that the probability of a fire is the same for every room, the average distance that the guest who is worst situated must move is 45 m.

Physical differences within the hotel guest population need to be taken into account in assessing the movement time. Elderly people with certain physical disabilities can walk with a velocity of about 0.78 m/s (Shields et al., 1995). The movement time for an individual in the longer corridor, $t_{MCorr60}$, can therefore be assumed to follow a normal distribution N(37,6) seconds. This cover differences based on travel speed and location of the fire. For the 30 m corridor, $t_{MCorr30}$ has the following parameters, normal distribution N(20,3) seconds.

The movement time in the fire room, t_{MRoom}, is assumed to vary uniformly between 3 and 8 seconds. In the case in which the guest in the room on fire is awake and can run out of the room to push the alarm button the time spent in moving from the room to the button, t_{Button}, is uniformly distributed U(5, 15) seconds.

Table 1. Values for the risk calculation.

Variable	Distribution
α	Lognormal (0.02,0.01) kW/s^2
Us	Normal (1.35,0.11)
t_{Det1}	Uniform (120,300) s
t_{Det2}	Lognormal (15,3) s
t_{Inv}	Lognormal (60,15) s
R_{Fire}	Lognormal (15,3) s
$R_{Neighb1}$	Lognormal (120,20) s
$R_{Neighb2}$	Lognormal (60,30) s
t_{MRoom}	Uniform (3,8) s
t_{Button}	Uniform (5,15) s
$t_{MCorr30}$	Normal (20,3) s
$t_{MCorr60}$	Normal (37,6) s

RESULTS

The resulting values of the reliability index β for the different subscenarios are presented in Figure 3 together with the corresponding values of the probability of failure. The figure shows the reliability using the limit state function with its basic variables, no consideration being taken of the likelihood of the events. As can be seen from the left figure, some results ended up as negative values. This is equivalent to a probability of failure higher than 50 %, cf. the right figure. Note the relationship between the β-value and the probability of failure in Eq. [3].

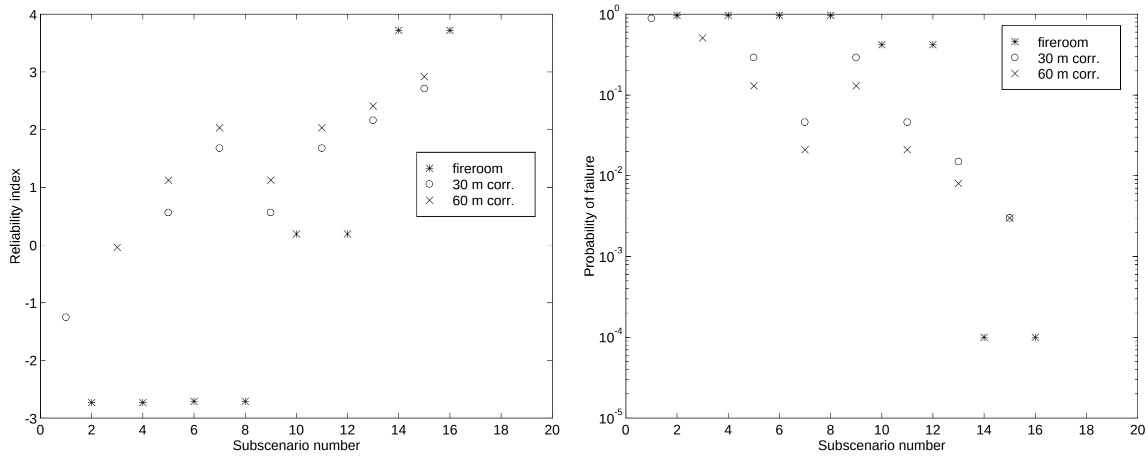

Figure 3. Reliability index β and probability of failure for all subscenarios.

One result that might seem unrealistic is that the longer corridor results in higher β-values. One might well expect that the more people using the corridor, the more unsafe the conditions would be. This expectation would result in the β-value being lower. Yet since the volume of the corridor is much greater in the case of the longer corridor, the time until untenable conditions are reached is still much greater there than for the shorter corridor. This result also expresses the fact that the number of persons involved does not affect calculations of the reliability. It is assumed that no queuing at the doorways will occur, the movement time depending only on the time for walking to reach the door. The number of persons involved is not considered in obtaining this time.

Three examples are shown in which the reliability measures are presented together with the corresponding branch probabilities. Since many of the estimates of branch probabilities are chosen on the basis of limited statistical information, the results should be seen as only illustrative. They can be used nevertheless to compare different design solutions with each other, even if the true safety level achieved may be incorrect. The cases presented differ in design solution, in installations and in assigned probabilities. For the subscenarios in which the reliability index is less than 0, the value 0 will be used instead, Figure 4.

Case 1

Hotel having 30 m corridors with rooms on both sides.
Probability that a person in a guest room will not wake up is 90 %.
Automatic fire detection system containing smoke detectors has been installed, one with an operational probability of 95 % (including the reliability of the alarm bell).
Escape alarm with alarm bells in the corridor, but no alarm in room that is on fire.
Subscenarios that are applicable in the event tree: 1, 5 and 13.

Case 2

Hotel having 30 m corridors with rooms on both sides.
Probability that a person in guest room will not wake up is 90 %.
Automatic fire detection system containing smoke detectors has been installed, one with an operational probability of 95 % (including the reliability of the alarm bell).
Escape alarm with a light and sound alarm in every room.
Subscenarios that are applicable in the event tree: 3, 7 and 15.

Case 3

Hotel with 30 m corridors and rooms on both sides.
Probability of person in guest room not wakes up is 90 %.
An automatic fire detection system with smoke detectors with an operational probability of 90 % (including the alarm bell reliability) is installed.
Use of an escape alarm providing both a light and a sound signal.
Subscenarios which are applicable in the event tree: 3, 7 and 15.

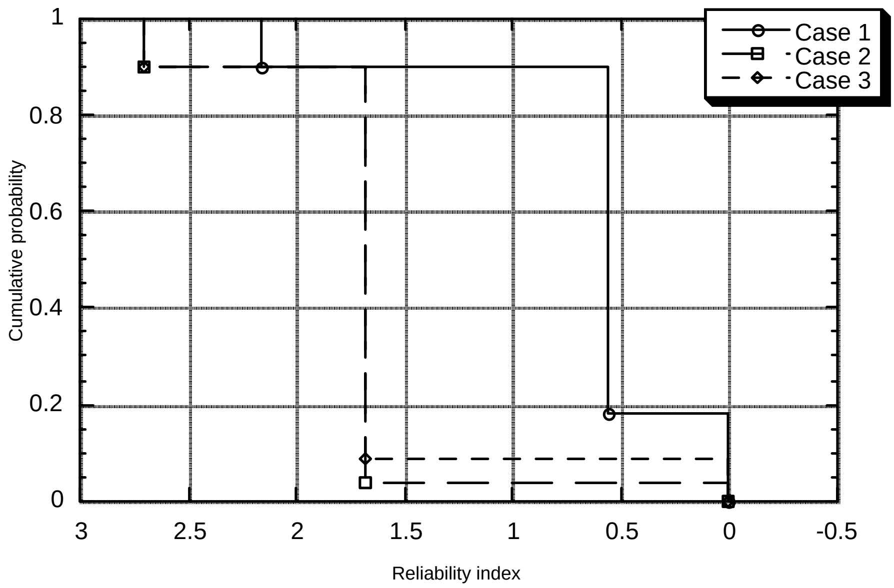

Figure 4. Reliability diagram for cases 1, 2 and 3.

IMPORTANCE OF VARIABLES

The relative importance of the variables in each subscenario was also calculated. The results are presented in Figure 5.

As it can be seen, the most significant variables are the fire growth rate and the model uncertainty parameter. Since these two variables are the only ones which determine the available time, they appear to be highly important. The walking times of the guests are variables of minor importance. Variations in these do not affect the reliability to any great extent.

For the corridor cases, the response times of the guests in the neighbouring rooms appear to be of some importance. This can be explained by the choice of parameters and the reasons for choosing them. Having better escape alarms resulted in lower response times, decreasing the importance of the variable just referred to.

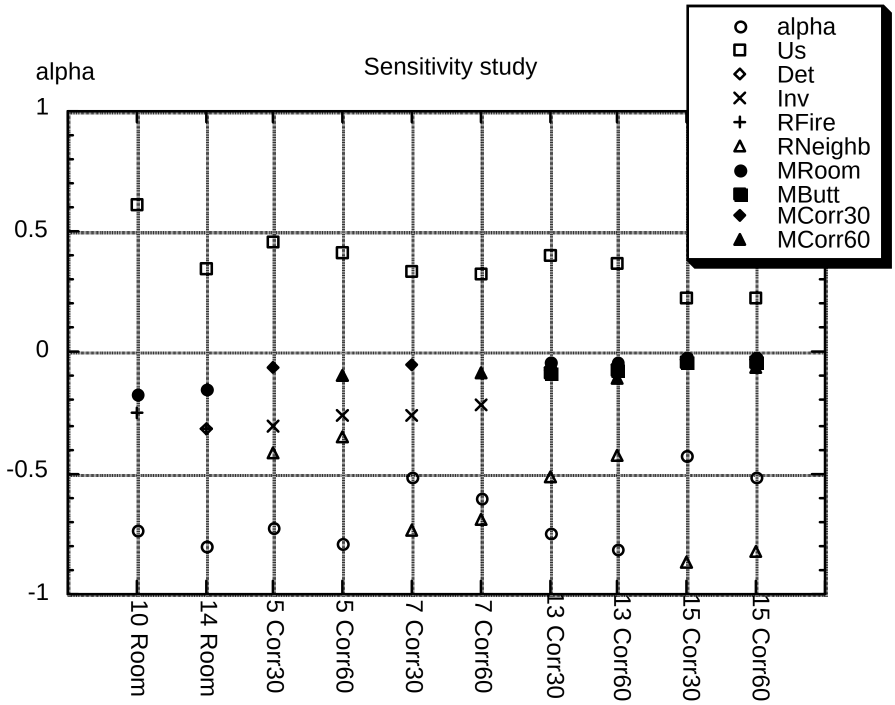

Figure 5. Importance of basic variables.

CONCLUSION

The individual risk method, i.e. the β-method, has been used in the area of structural engineering for almost 20 years. Nevertheless, the present study is one of the first attempts to treat the life safety of persons in buildings in which a fire occurs by use of this method. The method has been shown to result in consistent reliability, independent on how the limit state function is formulated. It is shown in this paper that it can be used to compare different design alternatives and that it provides arguments applying to choice of the safest alternative.

The most obvious disadvantage of the method is that it does not provide information concerning the frequency distribution of the limit state function. This information is needed to accurately, predict the risk to society.

A number of general conclusions regarding the safety of guests in hotels, involving principles possible to apply for practical purposes, can be stated:

- The door between the guest room and the corridor is important. If that door can be kept closed during a fire in the room, no untenable conditions will occur in the corridor. It is important, therefore, to maintain the fire-separating ability of the door and to secure the operation of the door closing device.

- The ability of the automatic fire alarm to detect a fire is essential for safety. The automatic fire detection system is necessary if the person in the guest room which is on fire is to be able to escape. For this person's safety, a direct alarm signal should be provided in the room. The signal should start as soon as the fire is detected.

- The most important variable is the fire growth variable α. This has to do with the large uncertainty connected with this variable. Reduction of this uncertainty can be achieved, for example, by restricting the amount of combustible interior furniture.

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