Brandteknik
Lunds tekniska högskola
Lunds universitet

Department of Fire Safety Engineering
Lund Institute of Technology
Lund University

Report 5006

On Probabilistic Assessment of Life Safety in Building on Fire

Gunnar H. Kristiánsson

Lund 1997

On Probabilistic Assessment of Life Safety in Buildings on Fire

Gunnar H. Kristjánsson

A thesis submitted in partial fulfilment of the requirements for the degree
magister scientiarum

Supervisor:
Ragnar Sigbjörnsson, Professor
Environmental and Civil Engineering Department
Faculty of Engineering

University of Iceland
1996

ISSN 1102-8246
ISRN LUTVDG/TVBB--5006--SE

Keywords: *Fire engineering, life safety, evacuation of buildings, reliability methods, analysis of uncertainty, smoke development,* b*-index, Icelandic fire prevention regulation*

Cover: Maria L. de Ris

Layout: Gunnar H. Kristiansson

Figures: Gunnar H. Kristiansson

Department of Fire Safety Engineering · Lund Institute of Technology · Lund University

Adress/Address	Telefon/Telephone	Telefax	E-post/E-mail
Box 118 /John Ericssons väg 1	046 - 222 73 60	046 - 222 46 12	
S-221 00 LUND	+46 46 222 73 60	+46 46 222 46 12	brand@brand.lth.se

Abstract

This study deals with the assessment, using probabilistic methods, of people's fire safety in buildings. The problem is addressed by modelling the evacuation of people from the fire- and smoke-threatened area. The buildings considered are assumed to be designed according to the Icelandic fire prevention regulation. The following types of buildings have been chosen for analysis: a dance hall, a sports hall, an office, a school, a hotel and an home for the elderly. For each case, a limit state function simulating the life safety is constructed. These functions are expressed in terms of analytical smoke development models and evacuation models. The analytical smoke development model is derived using the computer model, HAZARD. The analytical evacuation models account for detection time, response and behaviour time as well as the time needed for movements to a safe area. Each parameter in the limit state functions is described by an appropriate probability distribution. The probability of accidents is assessed using the safety index method, FORM. The β-indices are calculated, using the computer program package, STRUREL, for each limit state function and the sensitivity of various parameters is checked in order to detect the most important parameters.

Contents

Acknowledgements

This thesis is submitted in partial fulfilment of the requirements for a masters degree from the Faculty of Engineering at the University of Iceland and is written under the supervision of Professor Ragnar Sigbjörnsson. A Masters Committee was established with the Chief of the Iceland Fire Authority, Mr. Bergsteinn Gizurarson, Dr. Björn Karlsson, lector at the Department of Fire Safety Engineering at the Lund Institute of Technology, Lund University, Sweden, and Professor Ragnar Sigbjörnsson, Faculty of Engineering, University of Iceland.

The results presented herein are part of a Swedish research project termed *Brandforsk S.65* which is being carried out by the Department of Fire Safety Engineering at the Lund Institute of Technology, Lund University, Sweden, in close co-operation with Professor Sven Erik Magnusson and Lic. in Engin. Håkan Frantzich.

The present work was supported by a grant from the *Education Fund of the Icelandic Fire Authority* which is greatly acknowledged.

1 Introduction

In recent years, great progress has been made in fire protection engineering. Progress in fire dynamics, developments in computer modelling in the field and research into people's behaviour in fire situations have led to a better understanding of what takes place in a building when fire breaks out. As a result, technology transfer is gradually taking place. Instead of deciding all the fire precautions empirically, i.e., from prescriptive codes, or with rules of thumb, some major decisions can be made on the basis of performance-based fire requirements in building codes (see, for instance, [1, 2, 3, 4, 5]. Performance-based codes, however, are constantly being developed, and much work is yet to be done in the very near future in this area.

In this paper, an effort is made to measure the life safety built into prescriptive codes (the Icelandic fire prevention regulation). The safety-index, β, which is directly linked to the probability of failure, P_f (see Section 2 on Methodology and theoretical background), is calculated for various types of occupancies. This is done in order to compare the safety-levels within the codes, depending on the activity and occupancy of various types of buildings. On the basis of these β studies, other β studies and studies, for example, of fire statistics and experience, partial coefficients [6] will hopefully be determined that will be used in design procedures for the fire protection of buildings.

2 Methodology and theoretical background

2.1 General

In the following the theory of reliability are used to assess the life safety in buildings on fire. The method applied is the so-called safety index methods. The safety index provides a simple measure to characterise the uncertainty involved. The method also provides the so-called design point which is the point in the space of basic variables that has the highest probability density of failure. The basic reference applied through out this paper is *Fire Safety Design Based on Calculations* [7], and several other reports in the life safety area (see the reference list) from the Department of Fire Safety Engineering at the Technical University in Lund, Sweden.

2.2 First Order Reliability Method

The failure probability of a componential failure set can be approximated to the first order using the so-called first order reliability method or FORM. Then it is assumed that the basic variables $\mathbf{X} = (X_1, X_2, ..., X_n)^T$ are characterised by the joint probability distribution function $F_{\mathbf{X}}(\mathbf{x})$ and the failure set is given as $g(\mathbf{X}) \leq 0$, with $g(\mathbf{X}) = 0$ representing the limit state. In the simplest cases, the state function has the form of ‘capacity’ minus ‘demand’, but any form in higher dimensions involving non-trivial function evaluations is possible. The joint distribution function $F_{\mathbf{X}}(\mathbf{x})$ can have an arbitrary form.

The assessment of failure probability is carried out as follows. The random vector $\mathbf{X}$ is transformed into an independent standardised normalised vector $\mathbf{U}$, i.e., by the transformation $\mathbf{X}=T(\mathbf{U})$, and the point of the limit state function with the highest probability density (the β-point) is located in the standardised normalised space (the U-space) by a suitable algorithm. Linearisation of the limit state function at this point then yields the following estimate of the probability of failure:

$$P_f = P(g(\mathbf{X})=0) = P(g(T(\mathbf{U})) \leq 0) = P(h(\mathbf{U}) \leq 0) \approx \Phi(-\beta) \qquad (1)$$

with $\Phi(\ )$ the standard normal distribution and β the so-called safety index. This indicates that the safety index β provides a measure of reliability. Thus the safety level in a design process can be described by this single parameter.

2.3 Reliability index b

The safety or reliability index, β, contains information about the margin of safety in the limit state function as well as about the uncertainty of the parameters in the limit state function. A simple example is a limit state function describing the safety margin:

$$G = S - L \tag{2}$$

where S is the supply 'capacity' and L denotes the 'demand' requirement. S and L are assumed independent variables with finite means and standard deviations. The system is functioning if the safety margin, G, is positive, i.e. the supply is higher than the demand, and the limit state is given as G = 0. The mean and standard deviation of the safety margin can be expressed as:

$$\mu_G = \mu_S - \mu_L \quad \text{and} \quad \sigma_G = \sqrt{\sigma_S^2 + \sigma_L^2}$$

If the following reduced variables are introduced:

$$U_1 = \frac{S - \mu_S}{\sigma_S} \quad \text{and} \quad U_2 = \frac{L - \mu_L}{\sigma_L}$$

the limit state function can be expressed as:

$$\sigma_S U_1 - \sigma_L U_2 + \mu_S - \mu_L = 0 \tag{3}$$

According to [8] the safety index can be expressed as:

$$\beta = \frac{\mu_S - \mu_L}{\sqrt{\sigma_S^2 + \sigma_L^2}} = \frac{\mu_G}{\sigma_G} \tag{4}$$

If the variables, S and L, are normally distributed, the safety margin G will also be normally distributed, $\Phi(\mu_G, \sigma_G)$. The reduced safety margin is defined as:

$$U_G = (G - \mu_G)/\sigma_G \tag{5}$$

Hence, it follows that this reduced safety margin is also normally distributed but following the standard normal distribution, $\Phi(0, 1)$. In this case it follows also that the probability of failure, P_f, can be calculated exactly as:

$$P_f = F_G(0) = \Phi\left(-\frac{\mu_G}{\sigma_G}\right) = 1 - \Phi\left(\frac{\mu_G}{\sigma_G}\right) = \Phi(-\beta_C) \qquad (6)$$

This implies that the safety index is an exact measure on the computational probability of failure. If the basic variables are non-normally distributed, or the limit state function is non-linear, the safety index will only be an approximate measure on the computational probability of failure.

The safety index β, introduced by Hasofer and Lind [9], is defined as the shortest distance from the origin to the failure surface in the normalised system. Hence, this index is sometimes termed the geometric safety index. This geometrical interpretation is displayed on Figure 1 for the safety margin given in Eq.(2).

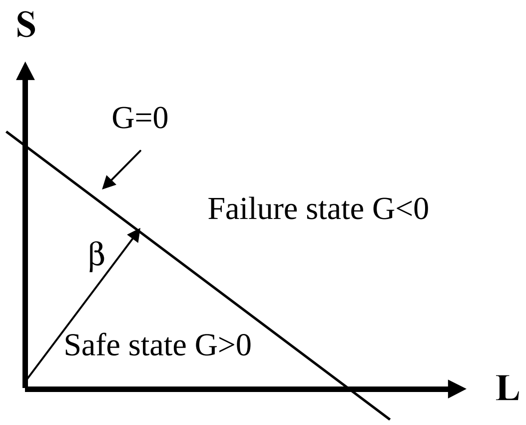


Figure 1 - Reliability index β in the two dimensional space.

In the general case the basic variables, $\mathbf{X} = (X_1, X_2, ..., X_n)^T$, define a n-dimensional hyper-space. In this space the limit state function, g(**X**), defines a hypersurface that divides the space into a safe region and an unsafe region (see Fig.1). If the basic variables are uncorrelated and normal distributed they can simply be mapped into standardised normal space by the Hasofer-Lind transformation:

$$U_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}}; \quad i = 1, 2, ..., n \qquad (7)$$

In the standardised normal space the safety index can be obtained as follows:

$$\beta = \min_{U_i \in h(U)} \sqrt{\sum_{i=1}^{n} U_i^2} \qquad (8)$$

Here, h(**U**) denotes the failure surface (the limit state function) in the standardised normal space.
The point on the failure surface which is closest to the origin is the point with the highest probability density of failure. This point is referred to as the design point. The co-ordinates of the design point can be expressed as follows [10]:

$$\mathbf{U}^* = (\beta\alpha_1, \beta\alpha_2, ..., \beta\alpha_n) \tag{9}$$

where the components of normal vector to the failure surface at the design point are given as:

$$\alpha_i = \frac{-\dfrac{\partial f(\beta\alpha_1,\ldots\beta\alpha_n)}{\partial U_i}}{\sqrt{\sum_{k=1}^{n}\left(\dfrac{\partial f(\beta\alpha_1,\ldots\beta\alpha_n)}{\partial U_k}\right)^2}} \tag{10}$$

For further description of the method, see, for example, [11, 7].

It is worth pointing out that the safety index may become negative (see for instance Section 5), which might seem to contradict the interpretation of the safety index as a distance in the standardised normal space. This occurs when the probability of failure is greater than 50 %. For a linear limit state function it is seen that the safety index becomes 0 when P_f is 50 %. Furthermore, when the normal to the failure surface does no longer point in the same direction as the state vector pointing to the design point the safety index becomes negative.

In order to calculate β and the probability of failure, P_f, the program package STRUREL [12] has been used. These programmes are discussed in the following section.

3 The program package STRUREL

3.1 Overview

The program STRUREL [12] is a computer package for probabilistic reliability analysis. It comprises four basic modules: COMREL, SYSREL, NASREL and STATREL. COMREL (COMponental RELiabilty) is a set of closely linked sub-modules covering time-invariant (COMREL-TI is the one we used in our analysis) and time-variant (COMREL-TV) reliability analysis of individual failure modes (components). SYSREL (SYStem RELiability) covers reliability analysis of multiple failure modes and allows the quantification of the effect of conditioning events. NASREL (Numerical Analysis and Structural RELiability) combines reliability analysis (COMREL) with the high performance, finite element program (NASCOM). STATREL (STATistics for RELiability) provides a rich set of techniques for the important preparatory steps of statistical data analysis and stochastic modelling.

3.2 COMREL

The core of COMREL [12] is a set of highly efficient and reliable search algorithms to find the β-point. The algorithms can run in so-called reverse communication, a feature which makes integration into other large, commercial computer codes very easy. Separate sub-modules have been designed for time invariant (COMREL-TI) and time variant (COMREL-TV) analyses, each having similar capabilities. The interface to the reliability problem is in terms of user-defined state functions written in FORTRAN with a specified interface. This interface is the same for all STRUREL programs. For many problems, pre-compiled libraries of state functions accompanied by a suitable set of stochastic models can be obtained on request or can be developed.

4 Characterisation of buildings and input data

4.1 Building types

The project includes five building types with different characterisations and different numbers of people with various abilities to move. These types are:

a) Dance hall, sports hall or equivalent assembly building
b) Office
c) School
d) Hotel
e) Home for the elderly

<u>a) Dance hall - Sports hall</u>

The fire precautions in the dance hall are defined in accordance with the Icelandic fire prevention regulation [13]. Many parameters are, however, varied, for example, the area and height of the building, the fire growth parameter (α) and the active systems, such as the detection system (with alarms) and sprinkler system that are installed in accordance with the regulation.

<u>b-e) Office, school, hotel and home for the elderly</u>

A similar procedure to the one for the dance hall was used. In order to simplify the calculations, the same layout was used for all these types. The layout is a relatively long corridor with joining rooms (see Figure 2). The parameters that are varied are, for example, the number of people (P), the response time (R), people's walking speed (V) and the detection time (alarm vs. no alarm), etc.

The layout was defined to be a corridor 50 m long (the maximum length allowed under the Icelandic regulation) with exits on both ends. The corridor is in all other respects designed according to the Icelandic fire prevention regulation [13].

4.2 Calculation model, input data and fire scenarios

The basic limit state equation, G, has been formulated as follows [7]:

$$G = S - D - R - E \geq 0 \tag{11}$$

where S is critical time (s) for smoke-filling to the height of 1,6 + 0,1 H (m); D is detection time (s); R denotes response and behaviour time prior to evacuation (s); and E is movement or evacuation time (s).

Figure 2 - Corridor with adjoining rooms.

In addition, modelling uncertainties, M_S, M_D and $M_{E,}$ have been introduced into the calculation, transforming equation (11) to the following expression:

$$G = M_S \cdot S - M_D \cdot D - R - M_E \cdot E \qquad (12)$$

where M_S is model-uncertainty for the smoke-filling model; M_D is model-uncertainty for the detection model; and M_E is model-uncertainty for the evacuation model. These parameters are described in the following.

Critical time, S

The critical time, S, is a measurement of how long it takes to produce critical conditions, i.e., the time it takes the smoke layer to reach a certain critical height.

The fire, in each case, is described by the classical heat output formula:

$$Q = \alpha t^2$$

where Q is the energy release rate of the fire (kW); α is a fire growth parameter (kW/s^2); and t is the time (s).

Formulas for S in the dance hall and sports hall are derived as a function of the height, area and fire growth parameter, α (see for instance [18]), one for the unsprinklered case and another for the sprinklered one. For the corridor cases, formulas are derived as functions of α. The fire program HAZARD [14] and regression from Excel [15] are used for this purpose (see Appendix A).

Detection time, D

Detection time is a measurement of how long it takes people to detect the fire from the time it starts. The detection time depends on whether there is a detection system or not. If there is a detection system, the detection formula is taken from [7] as functions of height and the parameter α. If there is no detection system, data is based on [16] and [3].

Response time, R

The response time is a measurement on how long after detection it takes people to react and begin to evacuate the building. The response time depends on the evacuation alarm and the size and layout of the building. The data are taken from [16] and [3]. In many cases, the input data are chosen with engineering judgement made by a group of experts in the fire science area.

Evacuation time, E

The evacuation time, E, is a measurement on how long it takes people to evacuate a building when they have decided to evacuate, i.e., the time it takes to travel to and through an exit. The time required for movement depends on the number of available exits, their width and the number of people in the building. The number of people depends on the type of building and the floor area. In some rooms, the number of people is fixed by the maximum number of people allowed by the regulation [13], but in others, the number could vary depending on the type of occupancy in the room.

4.3 Calculation inputs

Calculations for the halls fall into the following three categories:

1. Dance halls without a sprinkler or an alarm
2. Dance halls without a sprinkler, but *with* an alarm
3. Sports halls with a sprinkler and an alarm

These three cases are dealt with in the following.

4.3.1 Dance halls without a sprinkler or an alarm

Description and precautions:

The regulation requires an alarm in halls where more than 150 people are likely to congregate. There is 1 person per square meter in this case, so the building has been limited to 150 m^2 . All the linings on walls and ceilings are assumed to be in Class 2 (in accordance with DS 1065.2 [22]). There are two independent exits from the hall, i.e., one at each end. Fire extinguishers are placed near the exits.

Scenario

There is a dance in a small dance hall in Eskifjördur, a village in the eastern part of Iceland. When the most popular cha-cha-cha song begins, all the couples rush onto the dance floor. One of the guests has forgotten to put out his cigarette which lies in an ashtray. As it burns shorter, it falls down on the tablecloth which catches fire and begins to burn. The fire spreads out to the curtains, which are next to the table, and ignites the linings wall paper after a while. At this stage, an attempt is made to put out the fire with a fire extinguisher, but without luck. The people have already begun to evacuate.

Calculation model

The basic formula, i.e. the limit state function, is defined as earlier:

$$G = S - D - R - E \geq 0 \qquad (13)$$

using the same symbols as in equation (11).

The following formula is used for smoke-filling, S (see Appendix A):

$$S = 1.53 \cdot \alpha^{-0.26} \cdot H^{0.45} \cdot A^{0.55} \qquad (14)$$

where α is the parameter for growth of a fire (kW/s^2); H is the height of the room (m); and A is the area of the room (m^2). The probabilistic characteristics of the response time, R, has been assumed as follows:

R = triangular density (20, 30, 40)

This density is displayed on the following figure. The response time in the above case is relatively small as it involves a small, local assembly and, therefore, poses quite a threat to the people.

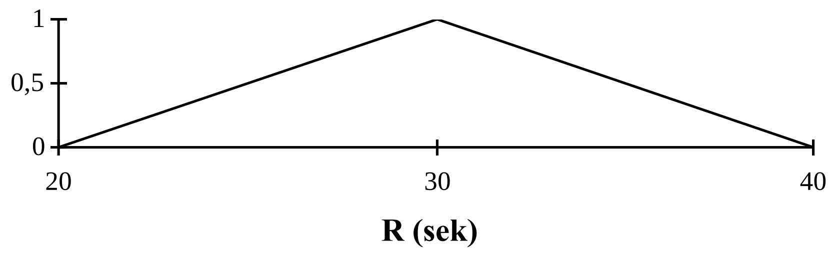


Figure 3 - Probability density of response time.

The detection time, D, has been assumed as follows:

D = triangular density (30, 45, 60)
which is also a relatively small time, compared with the table values in [16, 19, 3].

The alpha is assumed to follow the triangular distribution with parameters given as follows [20]:

α = triangular density (0.006, 0.012, 0.14)

The evacuation time is calculated from the formula [16, 3]:

$$E = \frac{N \cdot A}{F \cdot W} \qquad (15)$$

where N denotes number of persons per square meter (m^{-2}); A is area (m^2); F is number of persons going through a door per second per door-width in meters (m^{-1}); and W denotes width of door (m).

As the case is a small assembly room (up to 150 m^2) with two independent exits, the lower limit of the width of exits is: W = 1.8 m assuming the width of each exit to be at least 0.9 m, which is the minimum width for exit doors, according to the regulation [13]. Assuming the average number of people to be 1 person/m^2, as there are tables and chairs in the room, the following evacuation formula is gained:

$$E = 0.55 \cdot \frac{A}{F} \qquad (16)$$

The limit state formula is then:

$$G = (1.53 \cdot \alpha^{-0.26} \cdot H^{0.45} \cdot A^{0.55}) \cdot M_S - D - R - (0.55 \cdot \frac{A}{F}) \cdot M_E \quad (17)$$

Probabilistic properties of other parameters have been defined as follows:

M_S = normal distribution (1.35, 0.13)
M_E = normal distribution (1, 0.3)
H = rectangular distribution (3, 6)
A = rectangular distribution (50, 150)
F = constant (1)

The selection of M_S is based on [7] and Appendix A, while M_E is based on [7] and F on [21, 17].

4.3.2 Dance hall without a sprinkler, but with an alarm

Description and precautions

In this case, the upper limit of the fire section is 2000 m^2 without a sprinkler system, that is, in general, the upper limit in the regulation for a fire section on one floor without a sprinkler system. The lower limit here is set to 200 m^2. The building is equipped with an alarm system with smoke detectors and a direct line to a security service. The linings on walls and ceilings are in Class 1 (according to DS.1065.2 [22]). The building is also equipped with fire hoses which can reach into every corner. There are four exits with a total width, appropriate for the size of the space and the number of people (1 cm/person).

Scenario

There is a dance contest in a new dance hall in Reykjavík. A lot of guests are watching. Most of the tables and chairs have been stacked up at one end of the ball room. Spectators surround the dance floor. Suddenly, the a fire alarm sounds, alerting everybody to evacuate the building. A fire has started in a waste basket behind the stacks of tables and chairs. One of the visitors had thrown into a basket cigarette which he believed to be put out, but was apparently not. An attempt was made to put out the fire with a fire hose, but without luck.

Calculation model

Here, the same formula for smoke-filling as in 4.3.1 is used, but the detection time is calculated from the formula:

$$t_{act} = 5.36 \cdot \alpha^{-0.478} \cdot H^{0.7} \tag{18}$$

which was derived in [7].

As earlier the evacuation formula is:

$$E = \frac{N \cdot A}{F \cdot W} \tag{15}$$

According to the Icelandic fire prevention regulation [13], there shall be at least 1 cm of exit for every person in a hall, i.e.:

$$W = N \cdot A/100 \tag{19}$$

Then:

$$E = 100 / F \tag{20}$$

Some of the input data are the same as in 4.3.1, but the changes are as follows:

H = rectangular distribution (3, 9)
A = rectangular distribution (200, 1900)
M_D = Normal distribution (1, 0.2)
R = triangular distribution (20, 30, 40)

The response factor, R, has been linked to the size of the building as the size varies from 200 m^2 to 1900 m^2. Then:

$$R = R(1 + A \cdot 3/1900) \tag{21}$$

The limit state equation then becomes:

$$G = (1.53 \cdot \alpha^{-0.26} \cdot H^{0.45} \cdot A^{0.55}) \cdot M_S - (5.36 \cdot \alpha^{-0.478} \cdot H^{0.7}) \cdot M_D - R(1 + A \cdot 3/1900) - (100/F) \cdot M_E \tag{22}$$

<u>4.3.3 Sports hall with sprinkler and alarm</u>

Description and precautions

In this case, the fire section is more than 2000 m^2. The upper limit, though, is 5000 m^2. The upper limit by regulation is normally 6000 m^2 for a sprinklered fire section on one floor. The hall is equipped with an alarm with smoke detectors. The linings on walls and ceilings are in

Class 1 [22]. The building has fire hoses in suitable places. The number of exits is 4-6, with a total width appropriate for the size of the building.

Scenario

An exhibition is being held in Reykjavík sports centre. With all the equipment installed just for the exhibition, a faulty electrical cable starts a fire. As soon as the smoke detectors sound, a speaker system starts telling people to evacuate the building.

Calculation model

Here, a new formula for the critical smoke layer has been derived which takes into account the action of a sprinkler system (see Appendix A):

$$S = 0.34 \cdot \alpha^{-0.05} \cdot H^{0.455} A^{1.03} \tag{23}$$

The limit state equation, G, is then:

$$G = (0.34 \cdot \alpha^{-0.05} \cdot H^{0.455} \cdot A^{1.03}) \cdot M_S - (5.36 \cdot \alpha^{-0.478} \cdot H^{0.7}) \cdot M_D - R - (100/F) \cdot M_E \tag{24}$$

The input data that have changed from 4.3.2 are as follows:

M_s = normal distribution (1.35, 0.14)
A = rectangular distribution(2000, 5000)
R = triangular distribution(60, 240, 300)

4.3.4 Office

Description of the floor

The layout for the office is shown in Fig 2. As mentioned earlier, the same layout is used for an office, a school, a home for the elderly and a hotel. The floor is a 50-m corridor with adjoining rooms which serve here as offices. The corridor has exits at both ends, one to a staircase and another to the next fire section. The height of the rooms and the corridor is 3 m. The total size of the floor is 650 m^2, but the fireproof section is 600 m^2 as one of the end rooms and the staircase are fireproof.

Fire precautions

An office space on one floor is allowed to be up to 600 m^2 in one fireproof section in a multi-floor building and 1200 m^2 in a single-floor building. The building is a multi-floor building, so the fireproof section has been limited to 600 m^2. When an office space is divided into fire compartments that are less the 150 m^2 class 2 linings on walls and ceilings are allowed. This is not the case so the linings on the walls and ceilings are Class 1 (according to DS 1065.2 [22]). A fire hose is placed near the exits on both ends of the corridor. There are no emergency openings from the offices. No alarm is connected in the office as it is not required by the regulation.

Scenario

A fire breaks out in the coffee room (no. 13). Someone has forgotten to turn off the coffee maker. The machine contains no coffee and overheats, igniting the plastic. At this time, the staff smell something burning, and the person working in the room next to the coffee room rushes in. By that time, the fire has spread to a pile of paper next to the machine, generating a lot of smoke. The staff begin to evacuate the floor after an attempt to extinguish the fire with a fire extinguisher fails.

Calculation model

A formula was derived, with the help of the fire program HAZARD [14] and regression program in Excel [15] (see Appendix A), to simulate the development of a smoke layer in the corridor.

The adjoining rooms (offices) were defined to be open or closed, and a formula was derived for each case. One fire room was defined to be in the corner of the corridor (no. 13) and another in the middle of the corridor (no. 2). In all calculated cases, the fire rooms were assumed to be open (see Fig 4).

Figure 4 A model for derivation of formula for smoke-filling in the corridor.

The formula for smoke-filling (a function of α) describes when both exits have been blocked, i.e., when the smoke at the other end of the corridor has reached the critical height of 1,9 m. The same formula is used for all the cases with the same layout. The formula expresses a case of a fire in a corner room (no. 13). The door to the corridor and the doors to the adjoining rooms are assumed to be open.

$$S = 78.6 \cdot \alpha^{0.209} \tag{25}$$

Evacuation time is calculated from [3, 16]:

$$E = \frac{L}{V} + \frac{P}{F \cdot W} \tag{26}$$

where L is distance to an exit (m); V is people's walking speed (normal 1.3 m/s [16, 17, 3]); P is number of people; F is number of people per second. per m door (normal 1 persons/s/m [3, 16]); and W is effective door width (m).

The input data are as follows:

M_S = normal distribution (1.35, 0.11), (see [7] and Appendix A)
M_E = normal distribution(1, 0.2), (see [7])
α = triangular distribution (0.006, 0.012, 0.04), (see [20])
L = rectangular distribution (5, 50)
W = rectangular distribution (0.9, 1.6)
P = rectangular distribution (5, 70)
R = triangular distribution (20, 30, 40), (see [16,17])
D = triangular distribution (60, 150, 180), (see [16,17])

The limit state function is:

$$G = (78.6 \cdot \alpha^{-0.209}) \cdot M_S - R - D - \left(\frac{L}{1.3} + \frac{P}{W}\right) \cdot M_E \tag{27}$$

4.3.5 School

Description of the floor

In this case the same layout is used as for the office (see Fig. 2), the long corridor with adjoining rooms, except that instead of offices, the adjoining rooms are now school rooms.

Fire precautions

The fire prevention regulation [13] implies that every school room must be a fireproof room (at least EI-60) with at least EI-30 doors to the corridor. The door does not have to be self-closing or with a seal for cold smoke. The distance to an exit or another fireproof section (EI-60 with A-class linings according to DS 1065.2 [22]) is not supposed to exceed 25 meters. There shall be two independent ways out of a classroom. The layout is within these limits set by the regulation [13]. An emergency opening is supposed to be in every classroom, at least one for every 10 students. This means that each classroom has two emergency openings. The linings on the walls and ceilings are Class 1. A fire hose is placed near the exits on both ends of the corridor. The school is also equipped with a detection system with an alarm and a line to a security service which is required by the building regulation [24].

Scenario

After a break, the school bell rings for the students to enter the classrooms. One student who has been secretly smoking puts out his cigarette and sticks it in his coat pocket. He hangs the coat up with several other coats and rushes into his classroom. The cigarette is not quite out yet and ignites the coat. After a while the alarm goes off. The teachers tell their students to evacuate the building at once. When one of the teachers enters the fire room, the fire and smoke is too heavy, and he decides to evacuate the building and wait for the fire brigade to arrive.

Calculation model

The formula for critical smoke layer (S) is the same as for the office, as the same layout is being used, and the formula for evacuation (E) is also the same. The difference between these cases is that here a detection system is installed, required by the Icelandic building regulation [24] for all schools.

The activation time is taken from [7]:

$$t_{act} = 5.36 \cdot \alpha^{-0.478} \cdot H^{0.7} \qquad (27)$$

and with H = 3 m:

$$t_{act} = 11.6 \cdot \alpha^{-0.478} \qquad (28)$$

The input data are as follows:

M_S = normal distribution (1.35, 0.11), (see [7] and Appendix A)
M_E = normal distribution(1, 0.3), (see [7])
M_D = normal distribution (1, 0.2), (see [7])
α = triangular distribution (0.006, 0.012, 0.018), (see [20])
L = rectangular distribution (5, 50)
W = rectangular distribution (0.9, 1.6), (see [13])
P = rectangular distribution (110, 160)
R = triangular distribution (20, 30, 40), (see [32])
V = constant (0.6), (see [16])

It can be seen that the input data are much the same as for the office, except for P, V and α.

The limit state equation is:

$$G = (78.6 \cdot \alpha^{-0.209}) \cdot M_S - R - (11.6 \cdot \alpha^{-0.478}) \cdot M_D - \left(\frac{L}{V} + \frac{P}{W}\right) \cdot M_E \qquad (29)$$

4.3.6 Home for the elderly

Description of the floor

Here, the same layout is used (see Fig. 2) as for the school and office, but now we have elderly people living in the adjoining rooms, people who are taken care off by nurses and other staff. Most of the people can move around, some are, however, in wheel chairs. Some people need assistance as they do not know the way out.

Fire precautions

Each room in the corridor is EI-60 with EI-30 doors (without a self-closing device, and without a seal for cold and hot smoke as these are not required by the regulation [13]). As in the school case, the home is equipped with a detection system with an alarm and a line to the fire brigade. The linings on walls and ceilings are in Class 1. A fire hose is located at each end of the corridor.

Scenario

The old people are sitting in a living room watching television. Suddenly, the tv ignites. No nurse is in the room. One old man reaches the bell and rings for assistance. A moment later the alarm bell sounds. A nurse comes running and helps the ones who are left in the room to evacuate, along with other people on the floor. A moment later, one of the nurses tries to put out the fire with a fire extinguisher, but it has reached the curtains and the newspaper pile on the table and the smoke is too heavy. The nurses decide to evacuate the floor and wait for the fire brigade.

Calculation model

The limit state formula is the same as for the school. As there is no emergency exit from the rooms, we assume that people evacuate along the corridor and into the staircase. The smoke flows from the room of origin (no. 13), to the corridor and into the rooms which are assumed to be open and without self-closing devices.
The limit state equation is the same as for the school:

$$G = (78.6 \cdot \alpha^{-0.209}) \cdot M_S - R - (11.6 \cdot \alpha^{-0.478}) \cdot M_D - \left(\frac{L}{V} + \frac{P}{W}\right) \cdot M_E \tag{30}$$

The input data are much the same as for the school except following:

P = rectangular distribution (13, 26)
R = triangular distribution (60, 120, 240), (see [16])
V = rectangular distribution (0.3, 0.8), (see [16])
α = triangular distribution (0.001, 0.005, 0.01), (see [25,20])

4.3.7 Hotel (a)

Description of the floor

In this case, the layout is the same as earlier, but, the adjoining rooms are now hotel rooms (see Fig. 2).

Fire precautions

Each hotel room is supposed to be a fireproof room with EI-60 walls and EI-30 doors. The doors do not have to be self-closing or with a seal for cold smoke according to the regulation [13]. There is no requirement in the regulation [13] for an emergency opening from the rooms. The linings on walls and ceilings are Class 1 [22]. Fire hoses are at both ends of the corridor.

A detection system (with smoke detectors) is installed with an alarm and a line to the fire brigade.

Scenario

A hotel guest is going to sleep. He lies down on the bed with a cigarette in his mouth and is reading a book. He falls asleep and the cigarette ignites the bed. When the smoke alarm begins to sound, he wakes up. He runs out in the corridor, leaving the door open. He runs along the corridor and reaches the fire hose. When he enters the room, it is almost filled with smoke, and smoke is beginning to fill up the corridor, so he decides to evacuate the building without trying to put out the fire.

Calculation model

The limit state formula for the hotel is the same as for the school and the home for the elderly:

$$G = (78.6 \cdot \alpha^{-0.209}) \cdot M_S - R - (11.6 \cdot \alpha^{-0.478}) \cdot M_D - \left(\frac{L}{V} + \frac{P}{W} \right) \cdot M_E \qquad (30)$$

The input data that are new are as follows:

P = rectangular distribution (25,50)	
R = triangular distribution (60, 240, 300)	(see [16])
α = triangular distribution (0.006, 0.012, 0.04)	(see [20])
V = constant (1.3)	(see [16])

4.3.8 Hotel (b)

The layout is the same as in earlier cases. Instead of evacuating along the corridor, the guests decide to stay in their rooms and wait for the fire brigade as the corridor is filled with smoke when they open their doors.

The same smoke filling model is used with the fire in room 13. Simulating a closed door (EI-30) with a leakage equivalent to a 13-mm gap around the door [26,27].

The limit state equation for this case could look like this:

$$G = S - I \qquad (31)$$

where S is smoke-filling time to a critical amount of smoke in a closed room; and I is total rescue time of the fire brigade.

If I = 20 min. is assumed (with an 8-10 min arrival time), as suggested in the New Zealand fire code [4], P_f would be expected to be less than the one calculated, assuming evacuation along the corridor.

Given that there will be no flash-over in room 13, the room in question, no. 3, which is near the fire room, should be relatively free of smoke if one assumes that the fire brigade can put out the fire, smoke ventilate the corridor and rescue the people within 20 min.

It is of interest to take this solution into account. If a seal for cold smoke is put around the door, the leakage is about 10 times less than without a seal [27].

5 Results of calculations

5.1 Probability of failure

The probabilistic models described in the preceding section have been inputted into the program system STRUREL for assessment of safety index and probability of failure. The results are given in Table 1 below.

Table 1 - Safety index β and probability of failure P_f

Types of buildings	β	P_f (%)
Dance hall:	-0.46	67.7
Dance hall with an alarm:	1.66	4.9
Sports hall with a sprinkler and an alarm:	8.33	≈ 0
Office	0.59	27.8
School	-0.18	57.1
Home for elderly	-0.39	65.2
Hotel	-1.26	89.6

5.2 Sensitivities of parameters

It is possible by means of the program package STRUREL to evaluate the so-called sensitivity factors (see Appendix B and Section 2). These factors are important to assess the importance of the variables. The pie charts below show the sensitivity of the variables. For convenience, the list of parameters is as follows:

M_S = model uncertainty for the smoke-filling model
R = people's response time
H = height of the room
M_E = model uncertainty for the evacuation model
M_D = model uncertainty for the detection model
A = size of the fire compartment
α = fire growth parameter
D = detection time
L = length to an exit
W = width of exits
P = number of people
V = peopleís walking speed

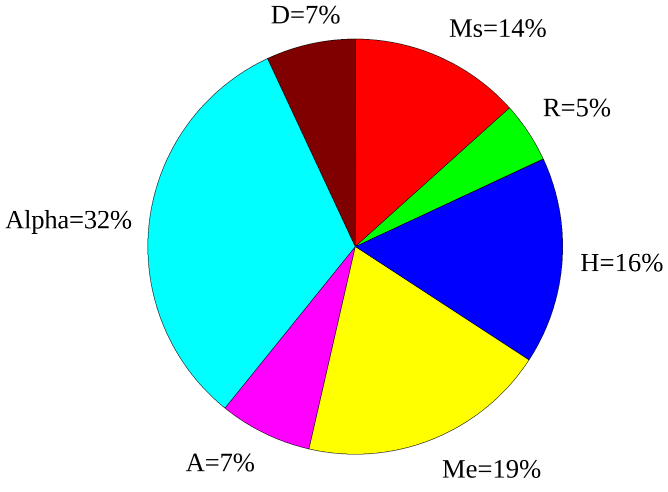


Figure 5 - Dance hall without a sprinkler and alarm.

Figure 5 demonstrates that alpha is the most sensitive parameter defined to be from 0.006 to 0.14, which is higher than for the other cases. In this case the linings are Class 2 on walls and ceilings, which can raise the fire growth rate substantially (see parameter study for this case). The model uncertainties are quite sensitive (33% of the total sensitivity), suggesting that the model is, in fact, quite inaccurate, and β is unstable with regards to model uncertainties.

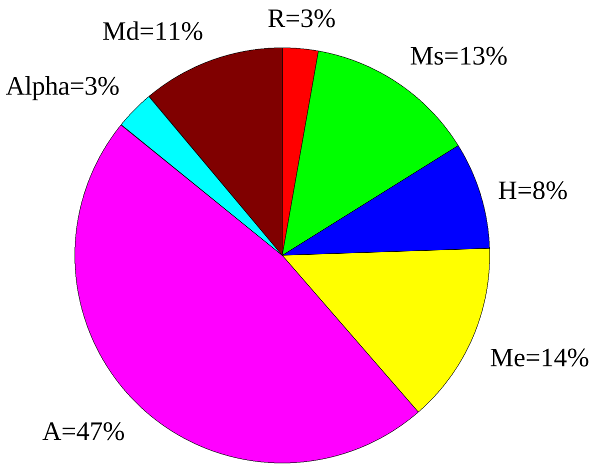


Figure 6 - Dance hall without a sprinkler, but with an alarm.

Figure 6 demonstrates that the area is the most sensitive factor. The area has a wide, uniform distribution from 200 m^2 to 1900 m^2. As the size of openings is a function of number of people, safety increases with increasing area as smoke-filling is a longer process for larger areas. Alpha is not so sensitive, i.e., whether it is 0.006 kW/s^2 or 0.04 $kW/s^{2.}$ This is, in fact, a remarkable result, compared with the one in Fig. 5. The response of people has been defined quite narrowly, so the sensitivity of R is not so big. Sensitivities of model uncertainties are quite high, 14% of the total for the evacuation model, 13% for the smoke-filling model and 11% for the detection model. Together all the sensitivities of the model uncertainties are 38% of total sensitivity, or approximately 1/3.

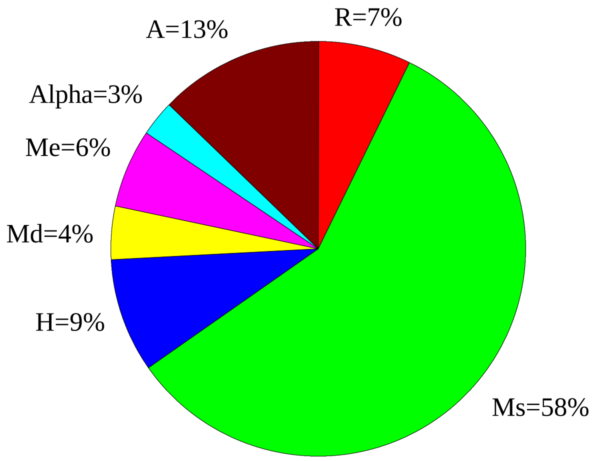


***Figure** 7* - Sports hall with a sprinkler and an alarm.

From Figure 7 one can see that sensitivity of model uncertainty of the smoke-filling formula is the most sensitive parameter. In this case, the β factor (equal to 8.33) is very high, leaving P_f very close to zero. Why is this? A possible explanation is the following: The area is very large, and the smoke-filling model distributes the smoke uniformly at the ceiling. Due to the large area and the effect of sprinklers, it takes a very long time to create a hazardous situation. The sensitivity of the smoke-filling parameter (S) becomes much higher because S is much bigger than the other parameters. It can also be seen here that the α factor is of less importance.

In the smoke-filling formula, the activation of the sprinkler reduces the rate of heat release (RHR) to 10% of the maximum RHR. This is questionable. We studied the effect of changing this in the parametric study.

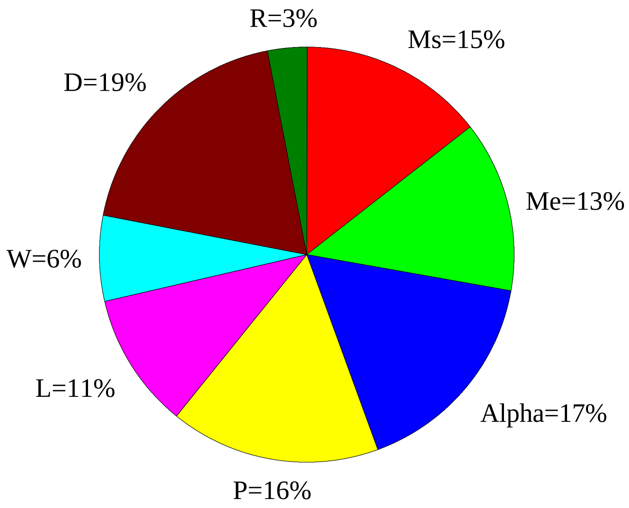


Figure 8 - Sensitivity in parameters for an office.

From Figure 8, it can be seen that the parameter sensitivities are quite uniformly distributed. The sensitivity of the fire growth parameter is greater than in the other cases, even though the distribution of the parameter is similar. The reason is probably that there is no detection system. The sensitivity of the detection parameter is also considerable.

The width of exits is less important, as is the length to an exit, even though the distribution of number of people is quite wide, from 5 to 70 people.

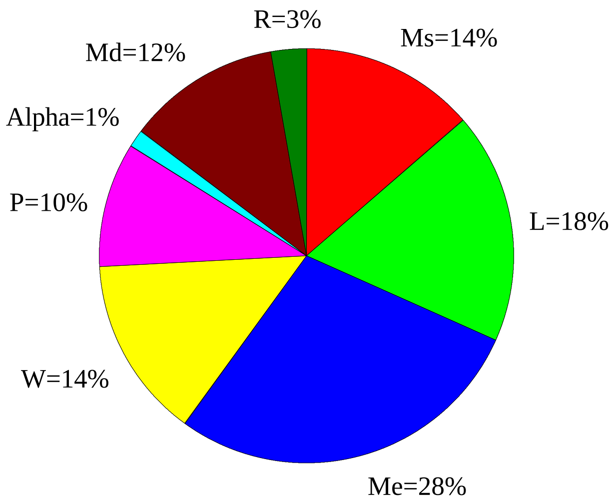


Figure 9 - Sensitivity in parameters for a school

Figure 9 demonstrates that the greatest sensitivity is the model uncertainty for the evacuation model and distance to an exit. This is not so surprising as there are lot of pupils in the class-rooms, assumed to be between 110 and 160. The sensitivity of door-widths is also greater than in the other cases for the same reason. The sensitivity of model uncertainties is here 54% of the total sensitivity.

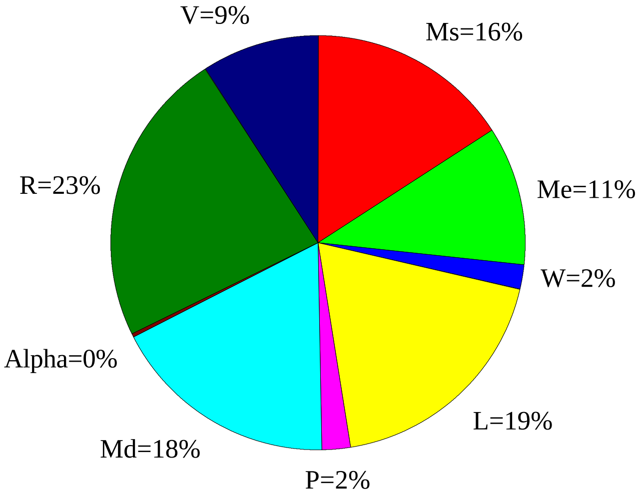


Figure 10 - Sensitivity in parameters for a home for the elderly.

The greatest sensitivity in the home for the elderly is the response factor (R), given a wide distribution from 60 to 240 seconds. The circumstances during the day are quite different from those at night. At night, there are fewer personnel, and the elderly people have to be awak-ened.

Notice that the distance to an exit is quite relevant as people are assumed to move very slowly. Sensitivities of model uncertainties are quite great, or up to 45% of the total sensitivity. Note here that the alpha factor, defined to be from 0.001 to 0.01, is of almost no importance.

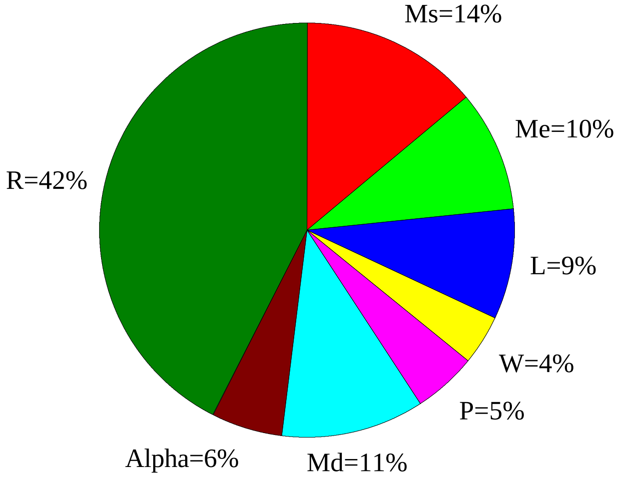


Figure 11 - Sensitivity in parameters for a hotel.

From Fig. 11 can be seen that response is the most sensitive factor, given a distribution from 60 to 300 seconds. The sensitivities of model uncertainties are 35% of the total sensitivities. The number of people, distances to exits (L) and widths of opening (W) are of less importance.

5.3 Summary of results and statistic

Dance hall without a sprinkler or an alarm ($50m^2$ - $150m^2$):

Probability of failure: 68 %
Most sensitive parameter: α (32 % of total sensitivities)
Second most sensitive parameter: M_E (19 %)
Total sensitivity of model uncertainties: 33 %

Dance hall without a sprinkler, but with an alarm ($200m^2$ - $1900m^2$):

Probability of failure: 5 %
Most sensitive parameter: A (47 %)
Second most sensitive parameter: M_E (24 %)
Total sensitivity of model uncertainties: 38 %

Sports hall with a sprinkler and an alarm ($2000m^2$ - $5000m^2$):

Probability of failure: ≈ 0 %
Most sensitive parameter: M_S (58 %)
Second most sensitive parameter: A (13 %)
Total sensitivity of model uncertainties: 68 %

Office

Probability of failure: 28 %
Most sensitive parameter: D (19 %)
Second most sensitive parameter: α (17 %)
Total sensitivity of model uncertainties: 28 %

School

Probability of failure: 57 %
Most sensitive parameter: M_E (28 %)
Second most sensitive parameter: L (18 %)
Total sensitivity of model uncertainties: 54 %

Home for the elderly

Probability of failure: 65 %
Most sensitive parameter: R (23 %)
Second most sensitive parameter: M_D (18 %)
Total sensitivity of model uncertainties: 45 %

Hotel

Probability of failure: 90 %
Most sensitive parameter: R (42 %)
Second most sensitive parameter: M_S (14 %)
Total sensitivity of model uncertainties: 35 %

Comparison

In figure 12 and 13 comparison of sensitivities in parameters is demonstrated graphically.

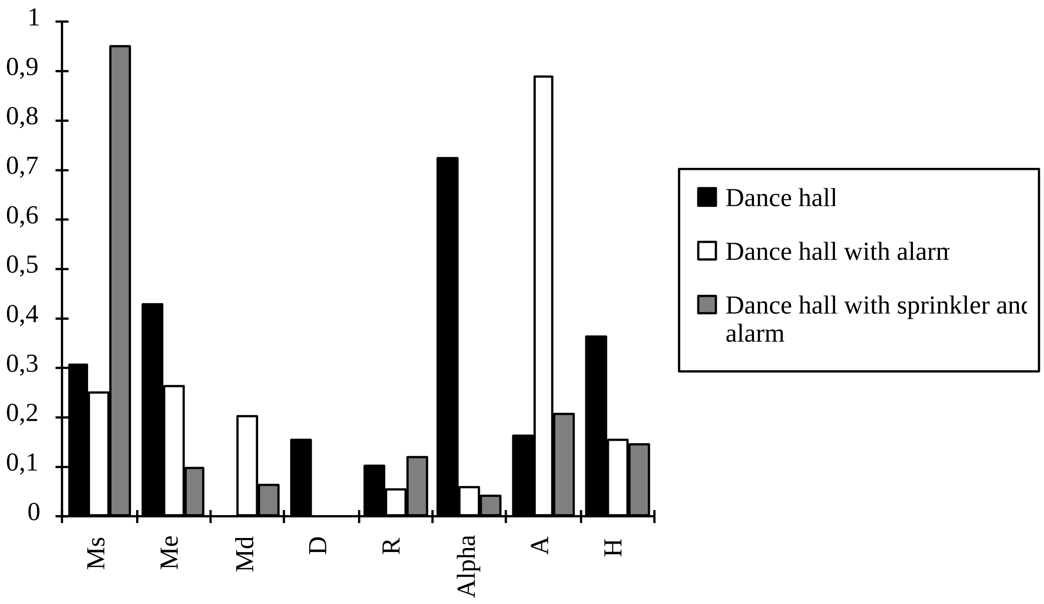


Figure 12 - Comparison of sensitivities in parameters

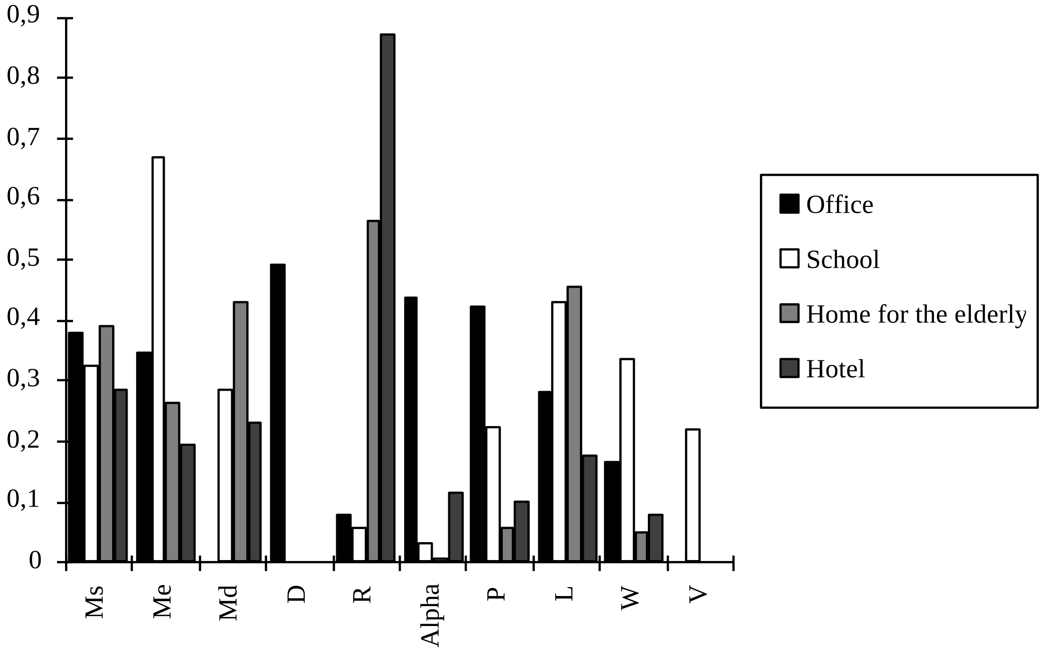
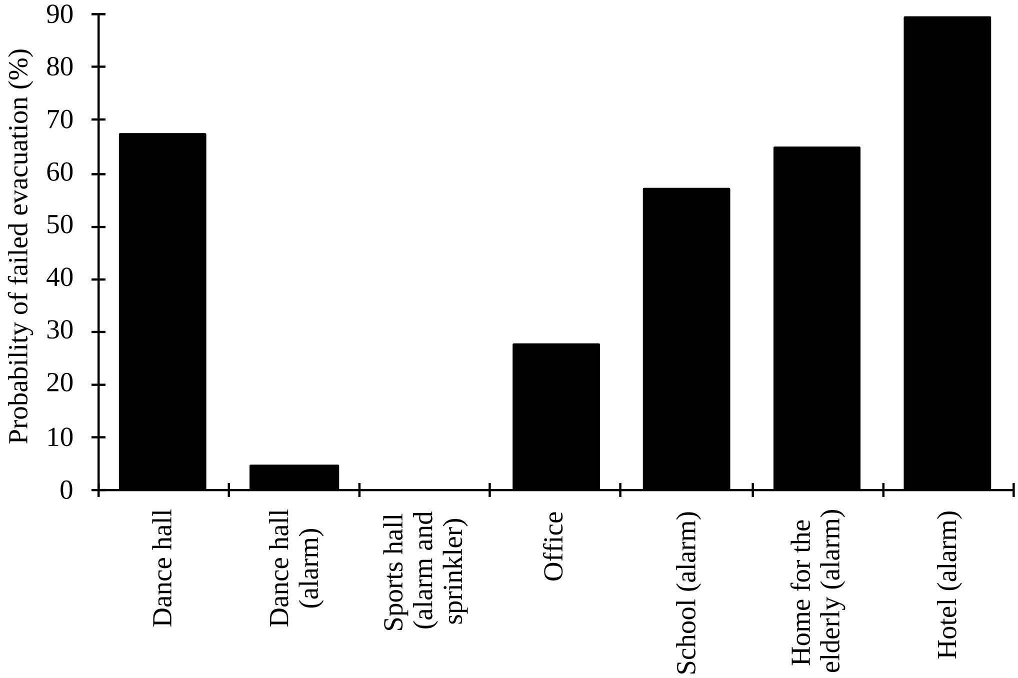


Figure 13 - Comparison of sensitivities in parameters

In figure 14 computational probability of failure for various occupancies is demonstrated graphi-



cally.

Figure 14 - Probability of failed evacuation for various occupancies.

In figure 15, the injury from fires in various occupancies in UK [30] is demonstrated. Notice the similarity of the looks of figures 14 and 15.

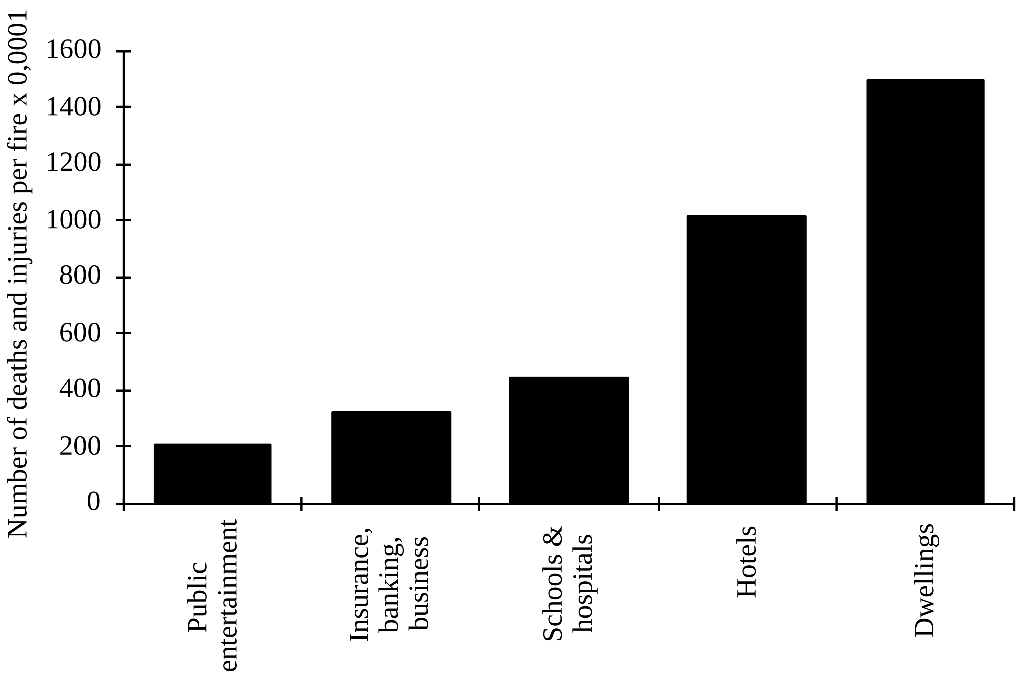


Figure 15 **- Injury rate per fire in various occupancies in UK [30].**

6 Parametric study

What happens if the parameter distributions are changed? How does β vary with the parameters? In the following cases, the most sensitive parameters and the effect of changing them are investigated for a few cases.

6.1 Dance hall without a sprinkler or an alarm

The most sensitive parameter in the small dance hall was the fire growth parameter, α, assumed to follow a triangular distribution (0.006, 0.012, 0.14) giving a safety index β = -0.462 (P_f = 67.7 %). Table 3 demonstrates how the safety index (β) varies with α.

Table 2 - Safety index, β, vs. fire growth parameter α

α	β	P_f (%)
0.006	1.89	2.9
0.01	1.18	11.9
0.05	-0.88	81.1
0.09	-1.60	94.5
0.13	-2.03	97.9

As can be seen in Table 3, changes in α parameter vary the probability of failure greatly.

The fire growth parameter is now assumed to have a little lower maximum value, for instance, a triangular distribution (0.006, 0.012, *0.04*). That leads to β = 0.44 and a probability of failure P_f = 33 %. Table 4 demonstrates how the probability of failure changes with height.

Table 3 - Safety index β vs. height of building

H	β	P_f (%)
3	-1,11	86.6
4	-0,68	75.2
5	-0,33	62.9
6	-0,04	51.6

Looking at the worst case with α = 0.14 kW/s^2 and H = 3 m, P_f is 99.7 %. Looking at best case with α = 0.006 kW/s^2 and H = 6 m, P_f is 0.1 %.

6.2 Sports hall with a sprinkler and an alarm

Variation of the smoke-filling formula

In the sports hall case, there was almost no probability of failure (β = 8,33 and a corresponding $P_f \approx 0$). The most sensitive parameter was model uncertainty for the smoke-filling model (58 % of the total sensitivities). The model resulted in a very high smoke-filling time, assuming the fire effect (kW) is decreased to 10 % of the maximum effect in 2 minutes when the sprinkler has been activated. Now the assumption was made that the effect was decreased to 50 % of the maximum effect in 4 minutes. Then, a new smoke-filling formula had to be derived with the same input data (see Appendix A, Table A.3).

Calculating the smoke-filling time (HAZARD [14]) until the smoke layer reaches 2.0 m for all combinations and using the regression function from Excel [15], the following smoke-filling equation was gained:

$$S = 0.27 \cdot \alpha^{-0.098} \cdot H^{0.31} \cdot A^{1.007} \qquad (32)$$

with the standard error of 11.3 %. This means that the total model uncertainty is:
M_S = normal distribution (1.35, 0.16). Putting this result into COMREL gives β = 6.70 with $P_f \approx 0$.

Variation of the evacuation formula

Just to demonstrate the unimportance of the evacuation model, the assumptions are changed. Earlier the exits were assumed to be 1 cm per person, with exits up to 100 m in width in a 5000 m^2 dance hall and 2 persons/m^2.

With changed assumptions i.e. a new smoke-filling formula and with 2 persons/m^2 and width of doors fixed to 24 m, β = 6.26 which still gives $P_f \approx 0$.

Putting the evacuation formula in general form the limit state formula becomes:

$$G = (0.27 \cdot \alpha^{-0.098} \cdot H^{0.31} \cdot A^{1.007}) \cdot M_S - (5.36 \cdot \alpha^{-0.478} \cdot H^{0.7}) \cdot M_D - R - (N \cdot A/F \cdot W) \cdot M_E \qquad (33)$$

Assuming the same input data as before:

M_E = normal distribution (1, 0.3)
M_D = normal distribution (1, 0.2)

H = rectangular distribution (3, 9)
A = rectangular distribution (2000, 5000)
R = triangular distribution (60, 240, 300)
α = triangular distribution (0.006, 0.012, 0.04)
F = constant (1)

with a new input data:

W = rectangular distribution (20, 50)
P = rectangular distribution (1, 2)
M_S = normal distribution (1.35, 0.16)

then $\beta = 6.51$ and $P_f \approx 0$

The sensitivities of the parameters are demonstrated in the following pie chart (Fig. 16). The figure demonstrates that the most sensitive parameter is still the model uncertainty of the smoke-filling model. The width of exits, which is commonly believed to be crucial, is of much less importance and of no more importance than the area (A), height (H) or the model uncertainty of the evacuation model (M_e) .

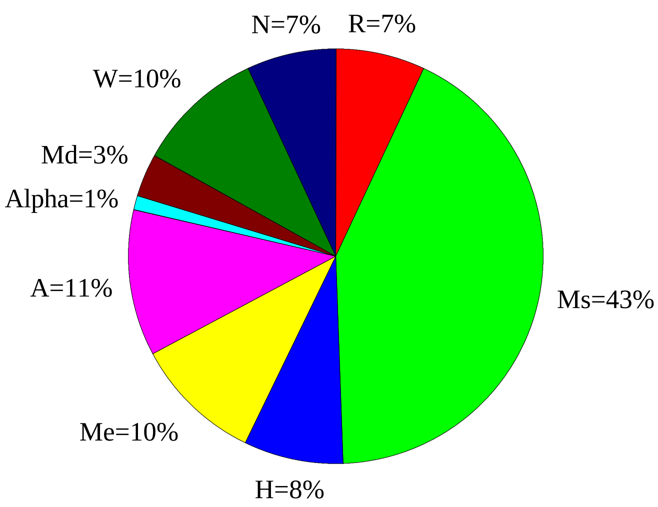


Figure 16 - Sensitivities of parameters

6.3 Hotel

Now look at the hotel case where P_f = 89,6 %, assuming the corridor to be used for evacuation. The most sensitive parameter was R, defined as triangular distribution (60, 240, 300).

Table 5 demonstrates how different distributions vary the probability of failure. From table 6 can be seen how P_f varies with different values of R.

Table 4 - Safety index vs. height of building

Distribution of R	β	P_f (%)
Normal distribution (240, 60)	-1.80	96.4
Rectangular distribution (60, 300)	-0.67	74.9
Lognormal distribution (240, 180)	-0.70	75.8

From Table 5 can be seen that changing the distributions does not have much influence on β.

Table 5 - Safety index vs. people's response time

R	β	P_f (%)
60	1.55	6.1
100	0.38	35.2
140	-0.84	79.9
180	-2.06	98.0
220	-3.19	99.9
260	-4.29	100
300	-5.34	100

Table 6 demonstrates that if the corridor is to be used for evacuation, the response must be within 100 seconds to ensure 'acceptable' reliability.

7 Discussions and conclusions

7.1 Discussions note

In the previous sections, the safety index β and probability of failure in cases of evacuation have been calculated giving us probabilities of failure from almost 0 in a big sports hall with a sprinkler system to almost 90 % for a hotel corridor, assuming evacuation along the corridor. This demonstrates that the safety level in the prescriptive fire prevention regulation is quite inconsistent.

The probability of failure which is supposed to simulate the probability of a failed evacuation is, of course, not the probability of a death in the case of each fire. Some assumptions have been made in our calculation. The following are few of them:

1. The fire could not be put out by a fire extinguisher or a fire hose.

2. In the corridor cases (hotel, school, home for the elderly, office) the evacuation has been assumed to be along the corridor to either of the two main exits. The emergency openings which are supposed to be in school rooms were not taken into account. People can also stay in their rooms and wait for the fire brigade if the room is a fire compartment. This matter was briefly discussed for the hotel case, stating that if people stayed put they would probably be more secure, assuming that the rescue time is within 20 minutes, and that the compartment and door is relatively tight (at least EI-30).

3. Despite every room opening onto the corridor being a fire compartment, the door to the corridor in the room on fire is assumed to be open, allowing the smoke to fill up the corridor.

These assumptions have been made, to be able to compare the results. The most important factors in each case have also been pointed out.

<u>Dance hall - Sports hall</u>

The results demonstrates that a larger hall (200 - 1900 m^2) with a detection system and an alarm is safer than a smaller hall (50 - 150 m^2) without either. The difference, though, is quite large, with P_f = 67.7 % for the smaller hall vs. 4.9 % for the larger one. Is this really the case? Why is the difference so big? Even though the detection and response time have been assumed to be quite small in the first case, the probability of failure is high, demonstrating that smoke-filling to a critical height is a very quick process in small assembly rooms. Is there a solution? Looking at the sensitivity pie chart one can see that the alpha factor is quite sensitive, compared with the other cases. This means that the probability of failure can be decreased, for example, by reducing the fire growth. This can be done by reducing the flammable interiors. For example, Class 1 linings should be prescribed in small assembly rooms, not only in the big ones where it is probably less critical.

The sensitivities of model uncertainties are also quite high. Based on this result, it can be stated that the result of P_f is quite inaccurate, i.e., P_f would probably be more precise with better evacuation and smoke development modelling.

It is also recognised that the safety of people increases with the size of a building as it takes longer for a design fire to fill larger houses with smoke.

A hall with a sprinkler and an alarm has a P_f of almost zero. What can be said about this case? Is a big sports hall 100 % safe for people? Of course not, but all systems have been assumed to be working 100 %, the alarm system, sprinkler system and exits. This, of course, may not be the case.

Office, school, home for the elderly, hotel

From these cases it can be seen that hotels are the most insecure places to be and offices the safest. This is not so far from what one would expect (see statistics). Note also that the fire growth parameter is only significant in the office without an alarm, outcome as for the small dance hall. In a school with many students, the evacuation model is the most sensitive. In places where people sleep, like the home for the elderly and the hotel, the response factor is the most important. From the hotel case can be seen that if the response time is more than 100 seconds, the probability of a smoke-filled corridor is quite high. This underscores the great importance of self closing doors and smoke seals being installed on hotel room doors where rooms are not supposed to have emergency exits. The same applies to homes for the elderly, except that in this case, the presence of staff lowers the risk and facilitates evacuation.

7.2 Conclusions

What can be learned from the results in general? It is worth stressing the following findings:

1. The life safety level within buildings designed after the prescriptive fire prevention regulation [13] is quite inconsistent with a probability of a failed evacuation between 0 - 90 %.

2. Due to simplifications, assumptions and uncertainties in models calculated P_f is quite inaccurate but can be used for comparison.

3. The calculations indicate similar categorisation of life safety in various occupancies as statistics from the UK.
4. In small assembly rooms, reduction of the fire growth parameter is very important. People's safety can, for example, be increased substantially by using Class 1 linings instead of Class 2 as is allowed in an assembly building for up to 150 people.

5. The fire growth parameter is more critical in buildings without an alarm and sprinkler system, but less important in the ones having an alarm and a sprinkler.

6. People's safety increases substantially with the size of assembly rooms.

7. Widths of openings and the distance to exits are more important in buildings with lots of people.

8. Large assembly buildings with sprinklers are quite safe if all the fire precautions are working.

9. People in hotels should stay in their rooms and wait for the fire brigade if the corridor is filled with smoke. This could also apply to schools. It is very important that the doors to the corridor are self closing and with smoke seals installed (both for cold and hot smoke).

References

1. Draft British Standard guide to the application of fire safety engineering principles to fire safety in building. BSI 1995.

2. Fire Engineering guidelines, draft 5,0. Fire Code Reform Centre, Australia, 1995.

3. Nordic Committee for Building Regulation: *Performance Based Fire-safety Requirements and Technical Guidelines for the Calculation Process.* Working Report 1994:07.

4. New Zealand Fire Code. 1992.

5. The Swedish Building Regulations (BBR 94). National Board of Housing, Building and Planning, 1995.

6. Håkan Frantzich, Björn Holmquist, Johan Lundin, Sven Erik Magnusson, Jesper Rydén: 'Derivation of Partial Safety Factors for Fire Safety Evaluation Using the Reliability Index β Method'. To be published.

7. Sven Erik Magnusson, Håkan Frantzich, Kazunori Harada: *Fire Safety Design Based on Calculations. Uncertainty Analysis and Safety Verification.* Lund University, Lund 1995.

8. Cornell, C.A.: 'First Order Analysis of Model and Parameter Uncertainty'. *Proc. Int. Symp. on Uncertainties in Hydrol. Water Resours. Syst.* University of Arizona, Vol 2, pp 1245-1275, 1972.

9. Hasofer, A.M. and Lind, N.C.: 'An Excact and Invarient First Order Reliability Format'. *Proc. ASCE, J. Eng. Mech. Div.*, pp 111-121, 1974.

10. Thoft-Cristensen, P. and Baker, M.J.: *Structural Reliability Theory and Its Applications*. Springer-Verlag, Berlin 1982.

11. Ang, A. H-S., Tang, W.H.: *Probability concepts in Engineering. Planning and Design, Volume II*. John Wiley & Sons, 1984

12. STRUREL; A Structural Reliability Analyses Program System, Theoretical Manuel, COMREL & SYSREL users manuel. Reliability Consulting Programs, Munchen, 1995.

13. Icelandic fire prevention regulation (no. 269/1978).

14. Peacock, R.D Jones, W.W., Forney, G.P., Portier, R.W., Reneke, P.A., Bukowski, R.W., Klote, J.H.: *An Update Guide for HAZARD I Version 1.2. NISTIR 5410*, US Department of Commerce, National Institute of Standards and Technology, 1994.

15. Microsoft Excel 4,0a. Microsoft 1995.

16. Håkan Frantzich: *A model for performance-based design of escape routes, LUTVDG/TVBB 1011 SE*. Department of Fire Safety Engineering, Lund University, Lund 1993.

17. Utrymningsdimensionering (e: Design of escape routes). National Board of Housing, Building and Planning, Rapport 1994:10.

18. NFPA 92 B, Recommended Practices for Smoke Management in Atria Malls. NFPA Quincy, MA 1991.

19. Håkan Frantzich: *Varseblivningstid och reaktionstid vid utrymning (e: Times of detection and evacuation), LUTVDG/TVBB 3071 SE*. Department of Fire Safety Engineering, Lund University, Lund 1993.

20. Stefan Särdqvist: *Initial Fires, RHR, Smoke Production and CO Generation from Single Items and Room Fire Tests, LUTVDG/TVBB 3070 SE.* Department of Fire Safety Engineering, Lund University, Lund 1993.

21. Håkan Frantzich: *Utrymningsvägars fysiska kapacitet, Sammanställning och utvärdering av kunskapslaget (engelsk: Level of service in escape routes), LUTVDG/TVBB 3069 SE*. Department of Fire Safety Engineering, Lund University, Lund 1993.

22. DS 1065-2:1990: Fire classification - Coverings - Class 1 and Class 2 coverings. EQV NKB 15:1990.

23. Communication of the commission with regard to the interpretative documents of council directive 89/106/EEC (94/C 62/01).

24. Icelandic building regulation, no. 177/1992.

25. Engineering Analysis of the Fire Development in the Hillhaven Nursing Home Fire, NISTIR 4665. 1989.

26. Poul Erik Poulsen: *Smoke control door, test report*. National Institute for testing of materials, Denmark 1978.

27. Smoke development in buildings, STF25 A9044. SINTEF NBL, 1994.

28. Bragason F.: *Determination of modeling uncertainty for two fire models*. Department of Fire Safety Engineering, Lund University, 1994.

29. Evans, D.D., Stroup, D.W.: *DETACT, NBSIR 85-3167*. National Bureau of Standards and Technology, Gaithersburg 1985.

30. Malhotra, H.L.: *Fire Safety in Buildings*. Garston, Building Research Establishment, December 1986.

31. Hohenbichler, M. and Rackwitz, R.: ‘Sensitivity and Importance Measures in Structural Reliabilityí. *Civil Engineering Systems, 3*., pp 203-209, December 1986.

32. Meeting held by Professor Sven Erik Magnusson with Gunnar H. Kristjánsson, Håkan Frantzich and Johan Lundin, Department of Fire Safety Engineering, Lund University, Aug. 1996.

Appendix A - Derivation of the smoke-filling formulas

A.1 Formula for smoke-filling of the dance hall

A smoke-filling formula was derived in [7]. The input data used for those calculations were the following:

Table A.1 - Input values for the calculation of smoke-filling time

Parameters				
Floor area (m^2)	200	500	800	1600
Ceiling height (m)	3		5	8
Fire growth rate (kW/s^2)	0.001	0.005	0.01	0.02

All combinations of the values from table A.1 were calculated from HAZARD, giving the time of smoke-filling to a critical height of 2 m. With regression, the following formula was obtained [7]:

$$S = 1.67 \cdot \alpha^{-0.26} \cdot H^{0.44} \cdot A^{0.54} \tag{A.1}$$

The standard error was: 5.03%. The total model uncertainty was then derived with additional information from [28] as:

M_S = normal distribution (1.35, 0.11)

In this case the input data are as follows in Table A.2.

Table A.2 - Input values for the calculation of smoke-filling time

Parameters				
Floor area (m^2)	50	200	1000	2000
Ceiling height (m)	3	5	7	9
Fire growth rate (kW/s^2)	0.006	0.012	0.04	

Then calculating all combination of the table values in HAZARD and using the regression function in Excel, the following formula is obtained:

$$S = 1.53 \cdot \alpha^{-0.26} \cdot H^{0.45} \cdot A^{0.55} \tag{A.2}$$

with a standard error of: 6.9 %. The total model uncertainty then becomes:

M_S = normal distribution (1.35, 0.13)

As can be seen, the difference between Equation (A.1) and (A.2) is not great. The constant is the greatest change from 1.67 to 1.53 or 8.4%.

A.2 Formula for smoke-filling of the sports hall

In a similar way as in A.1, a smoke-filling formula was derived for the sports hall with sprinklers. Here, however, the fire growth is affected by the sprinkler. This is handled in the following way:

The rate of heat release (RHR) is assumed to be reduced to 10 % within 120 seconds after the sprinkler activation [7].

$$Q = \begin{cases} \alpha t^2 & \left(0 \le t \le t_{act}\right) \\ \alpha t^2 \left(1 - 0.9 \dfrac{t - t_{act}}{120}\right) & \left(t_{act} \le t \le t_{act} + 120\right) \\ 0.1\, Q_{act} & \left(t_{act} + 120 \le t\right) \end{cases} \qquad \text{(A.3)}$$

where t_{act} is the activation time of the sprinklers (calculated with the computer program DETACT [29]), Q_{act} is the rate of heat release at activation time.

The following input data in Table A.3 were used for these calculations:

Table A.3 - Input values for the calculation of smoke-filling time

Parameters				
Floor area (m^2)	2000	3000	4000	5000
Ceiling height (m)	3	5	7	9
Fire growth rate (kW/s^2)	0.0029	0.012	0.047	

Calculating the smoke-filling time until the smoke layer reaches 2.0 m for all combinations and using the regression function from Excel, the following smoke-filling equation was obtained:

$$S = 0.34 \cdot \alpha^{-0.05} \cdot H^{0.455} A^{1.03} \qquad \text{(A.4)}$$

with the standard error of 9.9 %. This means that the total model uncertainty is:
M_S = normal distribution (1.35, 0.14)

A.3 Formula for smoke-filling of the corridor

The smoke-filling formula for the office, school, hospital and hotel was also derived using the program HAZARD [14]. The corridor model was built as follows (see Fig. A.3). A fire was simulated with various values for α (kW/s^2) and time until the smoke layer in several parts of the corridor was down to a critical height of 1.9 m and the results plotted out. Then the regression function from Excel [15] was used to make a smoke-filling formula (S).

The following results given in Table A.4 were obtained from HAZARD [14].

Table A.4 - Smoke-filling time to 1.90 m vs. α

Fire room(FR):	13	13	13	13	**13**	2	2
Smoke room(SM):	8	7	7	5	**5**	8	6
Open/closed[1]:	cl	cl	op	cl	**op**	cl	cl
	Smoke	filling	time	to the (s)	height	1.90	m
α (kW/s^2)							
0.002	164	215	220	302	**292**	358	328
0.004	140	185	189	257	**249**	306	278
0.006	130	169	172	233	**233**	279	296
0.008	120	158	159	217	**215**	261	233
0.01	115	151	152	207	**201**	248	220
0.015	102	135	136	190	**192**	225	197
0.02	96	126	127	176	**177**	210	183
0.025	91	119	119	167	**168**	200	172
0.03	86	115	115	159	**159**	196	184
0.035	81	110	111	153	**153**	188	173
0.04	79	113	135	156	**158**	181	158
0.045	77	103	100	151	**154**	186	180
0.05	76	99	98	147	**151**	181	175

[1]Open/closed room means the other rooms in the corridor and not the fire room which is always assumed to be open

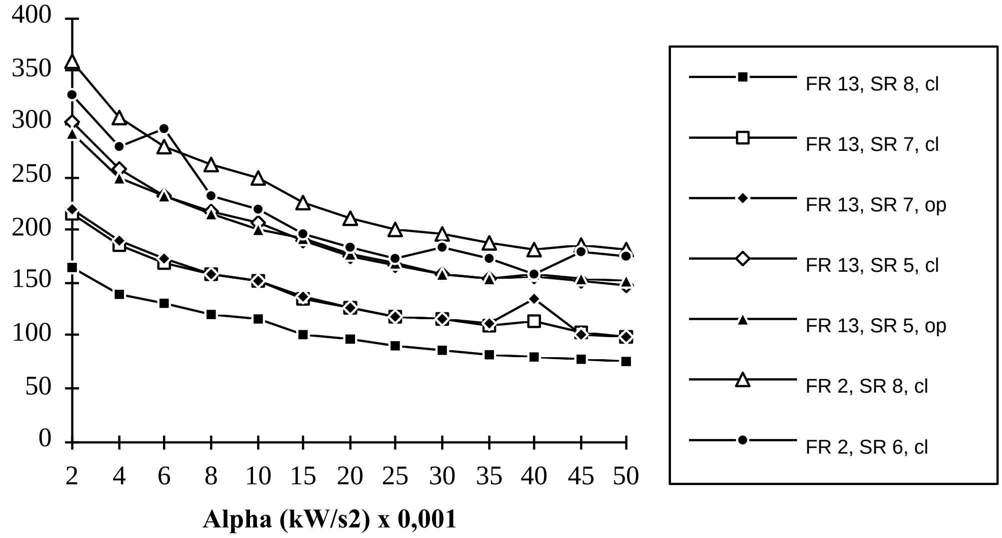


Figure A.1 - Smoke-filling time to 1.90 m vs. α

A formula with input data from fire room (FR) 13 and smoke room (SM) 5 with all rooms open was chosen as the smoke filling formula for all the corridor cases. The smoke filling formula is the following:

$$S = 78.6 \cdot \alpha^{0.209} \qquad (A.5)$$

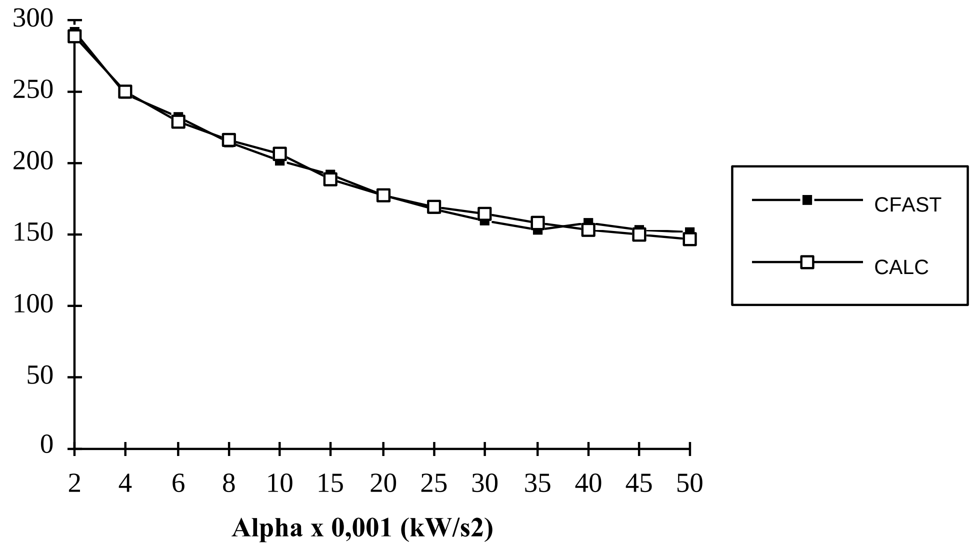


Figure A.2 - Comparison of smoke-filling times: cfast [14] vs. smoke-filling formula.

As can be seen in Fig. A.2 the smoke-filling formula is quite accurate, compared with the results from CFAST. The standard error is only 1.8 %. The model uncertainty then becomes: M_S = normal distribution (1.35, 0.11).

Figure A.3 - The corridor in HAZARD

Appendix B - Sensitivity and importance measures

In many cases the knowledge of sensitivity resp. importance measures can be very informative. The most of them are computed in the program package STRUREL [12].

If τ denotes a set of distribution parameters the probability of failure can be demonstrated as:

$$P_f(\tau) = \int_V f_X(x|\tau)\, dx \tag{B.1}$$

here $f_X(x)$ is the probability density of X and V is the so-called failure domain.

$$V = \{g(z_r, z_s) \le 0\} \tag{B.2}$$

Then the sensitivity of the failure probability with respect to parameter τ_k is defined as:

$$\alpha_{\tau_k} = \frac{\partial P_f(\tau)}{\partial \tau_k} \tag{B.3}$$

The sensitivity α_{τ_k} is also denoted an importance measure of the parameter $\tau_{k.}$. It is useful to relate such measures not to failure probabilities but to the so-called equivalent safety index.

First the componental case is considered, i.e., the failure domain V is bounded by only one smooth and locally at least once differentiable limit state function. Using the FORM result for P_f allows to define importance measures for the variables U_i in standard space at the β-point $\mathbf{U}^*$:

$$\alpha_E = \frac{\partial \beta_E}{\partial u_i} \frac{1}{\|\alpha_E\|} \mathbf{U}^* \tag{B.4}$$

Approximately and asymptotically one sets [31]:

$$\alpha_E = \alpha \tag{B.5}$$

where α denotes the normalizes U-space gradient of the state function at the β point.

The β_E values are measures of the sensitivity of the safety index β with respect to a shift of one of the U-variables. Therefore, they are denoted as α_μ´s in the sequel.

$$\alpha_{\mu_i} = \frac{\partial \beta_E}{\partial \mu_i} \approx \alpha_i \tag{B.6}$$

Furtheron, the α_μ´s can be interpreted as the relative importance of the U-variables in the state function and also as the relative importance of the X-variables (i.e., the non standard normal variables), provided that the X_i are independent.