Derivation of Partial Safety Factors for Fire Safety Evaluation Using the Reliability Index β Method

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ABSTRACT

A methodology for deriving design values for occupational safety in public buildings based on risk is presented together with an illustrative example. With knowledge of the design values and chosen characteristic values the corresponding partial coefficients are automatically defined. The characteristic values can be chosen as an upper 80th or 95th percentile of each distribution. The derivation of the design values is performed using a FOSM (First Order Second Moment) method. The safety level of the building is expressed as a value of the reliability index β. In the example case a target β-value is chosen to 1.4 which is approximately equivalent to a probability of failure of 8 % on condition that a fire has started.

KEYWORDS: fire, evacuation, partial coefficient, risk, reliability index, FOSM

INTRODUCTION

The fire safety regulations in several countries have during the last years undergone a change from being prescriptive to become more performance based. This means that the codes are telling what the objectives are but do not tell the designer how to solve the specific problems. Together with these new fire safety regulations several general principles or guidelines have been published or are to be published [1], [2], [3]. These guidelines are describing how to solve separate problems in the design process dealing with things such as the descent of the smoke layer in a room, the spread of smoke to neighbouring compartments, time for detection of the fire etc. The link between the submodels in the total design system is not so clear. In the British draft guide [1] a model is presented, describing data transfer between design subsystems with the aid of a central information bus, but much is still unclear regarding the practical use of the information bus.

What is absent in these documents are guidelines regarding methods to quantify and verify the safety levels generated in a specific design procedure. In some documents the safety is linked to values defined as characteristic values and safety factors called partial coefficients. In others so called global safety factors are proposed. It seems that from the discussion about risk in fire safety design arises a new set of questions to be answered such as

- how do we evaluate risk?
- how do different evaluation methods affect the outcome?
- what is the link between risk analysis and design?
- how should we choose design parameters?
- what background data is missing?
- what safety factors should we use?

etc.

This paper will try to answer some of these questions in showing the link between one risk analysis method and the performance based design procedure. This will be done by deriving partial coefficients for a class of buildings (public buildings) and corresponding characteristic values for the relevant parameters.

A general procedure outlining the methodology for deriving partial coefficients and other code parameters has been proposed in [4]:

- set limits on the range of scenarios for which the individual deterministic equation in the code will be applicable
- specify the deterministic functional relationships to be used as a basis for each design subprocedure
- characterize the major sources of uncertainty in models and input parameters
- select a suitable safety format - the number of partial coefficients and their position in the design equation
- select appropriate characteristic values to be used as fixed deterministic quantities in the code
- determine the magnitude of the partial coefficients to be used, together with the corresponding characteristic values, to achieve the required reliability (by judgement, fitting, optimization etc).

THE DESIGN PROBLEM

The design problem can be formulated in terms of the limit state function G as

$$G(X_1, X_2, \ldots, X_n) = 0. \tag{1}$$

The parameters X_i are stochastic parameters describing the system, for example fire growth rate and response time of occupants. The goal is to find a solution to this problem with the constraint that

$$P(G < 0) < p_{target}. \tag{2}$$

The design can be performed on different levels depending on the amount of information available [4], [5], [6]. On level 1 the reliability method only employ one "characteristic" value for each uncertainty parameter. The values of these parameters are chosen so they will result in a specified reliability. The calculations in this paper will be performed on the level 2 using the mean and standard deviation of the uncertainty parameters. The actual form of the respective parameter distribution will therefore not be considered. A level 3 procedure uses the complete information about the parameter distribution as well as the joint probability functions. A method on a lower level can only be verified by a higher level method. "Characteristic" values and partial coefficients on level 1 will in this paper be derived using the method on level 2.

Conceptually, the design problem is simple. Specify input data (deterministic and stochastic), choose a target reliability index β which connects the reliability to the target probability of failure, and vary the design parameters to be determined until the chosen value of β has been obtained. The process automatically provides the design vector $(x_{1,d}, \ldots, x_{n,d})$, with $x_{i,d}$ by definition being equal to the product of a characteristic value $x_{i,ch}$ and a partial coefficient γ_i:

$$x_{i,d} = \gamma_i x_{i,ch} \tag{3}$$

The problem is that the procedure requires specification of *all* input data. A functional, deterministic relationship in a design guide must be valid for a whole class of buildings with e.g. varying geometry. In addition, a design guide cannot simply refer the engineer to a level 2 method; a more simple and transparent method is required, in normal cases a deterministic, level 1 design equation. The solution to the problem is to derive, using an optimization procedure, values of $x_{i,d}$ and γ_i that fulfill two conditions:

- keep the *average* safety level constant for the whole class of buildings
- minimize the difference in the required and obtained safety levels, taken over all individual buildings.

In other engineering disciplines the design value $x_{i,d}$ is normally derived by a combination of a partial coefficient γ_i and some characteristic value $x_{i,ch}$ (50th, 80th or 95th percentile) from the relevant distribution.

To be able to use this approach two criteria have to be met:

- the function G must be possible to define
- statistical information of the variables X_i must exist.

The first statement is in this paper met by deriving response surfaces for the relevant expressions such as for the available safe egress time. The second statement cannot be met without expert judgement as much statistical data is lacking. This limits the application to some extent.

HOW IS RISK DEFINED?

In this paper we define risk as the product of probability and consequence of the event. The risk is divided in two levels

- the probability that a fire has started
- the probability that life-threatened conditions will arise before the room is evacuated and at least one person is trapped inside. The society risk is a combination of probability and number of casualties and is usually described with F/N-curves [7]. In the present case we are only interested in the individual risk i.e. at least one casualty, [4], [5], [6],[8].

The method used in this paper, deriving design values and partial coefficients, is the one known as the FOSM (First Order Second Moments) reliability index β method. This method provides the reliability index β which can be translated to the probability of failure of the system. It also provides the design point at which the probability of failure is highest. Using the values at the design point will result in a solution having the safety level indicated by the reliability index β. In references [7] and [9] a number of scenarios are investigated and design points evaluated.

RELIABILITY INDEX β

The safety level in a design process can be described by one parameter, the reliability index β. This index contains information about the margin of safety in the limit state function as well as the uncertainty of the parameters in the limit state function. An example of a limit state function calculating the margin $M = T - Q$ where T and Q are independent and having means and standard deviations. The parameter T can be interpreted as a strength variable and Q as a load variable. The system is successful if the margin is positive i.e. the strength is higher than the load. The mean and standard deviation of the margin can be described as

$$\mu_M = \mu_T - \mu_Q \quad \text{and} \quad \sigma_M = \sqrt{\sigma_T^2 + \sigma_Q^2}$$

One reliability index β_C is defined by Cornell [10] as

$$\beta_C = \mu_M / \sigma_M$$

If the parameters T and Q are normally distributed the margin M will also be normally distributed. The parameter $(M - \mu_M)/\sigma_M$ is $N(0,1)$ and the probability of failure, p_f, can then be calculated as

$$p_f = F_M(0) = \Phi(-\frac{\mu_M}{\sigma_M}) = 1 - \Phi(\frac{\mu_M}{\sigma_M}) = \Phi(-\beta_C) \tag{4}$$

using standard statistical textbooks and handbooks. If parameters are non-normally distributed or the limit state function is non-linear the relationship in Eq. 4 will only be approximate.

A better measure of reliability is the Hasofer-Linds index [8]. This is defined as the shortest distance to the failure surface when the parameters are standardized. This means that the origin of the system is transferred to the mean values and the variable distance is measured in standard deviations. Standardized parameters are calculated as $X' = (X - \mu_X)/\sigma_X$, see Figure 1 showing a two-dimensional case.

If the limit state function is non-linear, if the distribution of the parameters are non-normal or if the parameters in the limit state function are correlated an iterative procedure has to be used in deriving the reliability index β. We thus face a minimization problem. The procedure will result in the design point, the β-value and an estimate of the corresponding probability of failure.

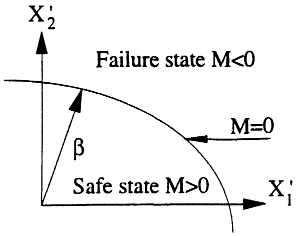

FIGURE 1: Reliability index β in the twodimensional case using a standardized space.

CALCULATION SCENARIO

The section provides the background for the numerical example in which the safety of people is examined. The escape time margin is used as the definition of safety. The limit state function is expressed as

$$G = S \cdot M_S - D - R - E \tag{5}$$

where
S = time to reach critical conditions in the room
M_S = model uncertainty
D = detection time of the fire
R = response and behaviour time of the occupants
E = movement time out of the room.

The time to reach critical conditions is derived using the CFAST model [11]. A set of combinations of floor area, room height and fire growth rate is used to calculate the time to critical conditions for each combination. With all the combinations and times a regression analysis was performed to get a metamodel predicting the time to critical conditions as a function of fire growth rate, α, floor area, A and room height, H. The fire is characterized as an αt^2-fire. The regression equation for time to critical conditions is

$$S = 1.67 \cdot \alpha^{-0.26} \cdot H^{0.44} \cdot A^{0.54} \tag{6}$$

The same procedure was made for the detection time using the Detact-t2 model [12], resulting in

$$D = 5.36 \cdot \alpha^{-0.478} \cdot H^{0.7} \tag{7}$$

The model uncertainty for the CFAST model was derived as $N(1.35, 0.1)$ [7]. The response and behaviour time is chosen to be a random variable with parameters presented in connection with the example, [13]. The movement time is calculated as

$$E = N \cdot A / (W \cdot F) \tag{8}$$

where
N is the number of occupants per square metre
W is the door width

F is the specific flow of occupants through the doorway.

The parameters in the limit state function are all random variables except the door width and the specific flow constant. The door width is the design parameter in the procedure described later and the specific flow constant is set to 1 person/m·s. The values describing the random variables are presented later in connection with the example.

DERIVING DESIGN VALUES FOR A CLASS OF BUILDINGS

As stated before the designer does not want to calculate the reliability index but rather use design values resulting in a solution with a given safety level. Partial coefficients and characteristic values produce design values which he/she can use to obtain the design parameter, in this example the exit door width. The design guide must cover a large group of buildings with varying conditions, in this example the floor area and room height. The design point then has to be derived using an optimization process covering the whole class of buildings [4].

The situation is the opposite from the one when the reliability index β is derived. Knowing the design values of the stochastic parameters and having determined the building floor area and room height, the door width is the wanted result, assuming that a specified β is achieved. The design values should be valid for the whole class of buildings with different floor areas and room heights. Suppose that the class of buildings is limited to buildings with floor areas between 1000 m^2 and 1600 m^2 and room heights between 3 and 8 m. The objective is to derive α_d, M_{Sd}, R_d and N_d so that the difference in safety level is minimized over the calculated cases. The cases in this example are the buildings with the following room height and floor area combinations; (3, 1000); (5, 1000); (8, 1000); (3, 1600); (5, 1600); (8, 1600). This results in six cases.

The purpose of the minimization is to find limit state functions, one for each building condition, such that the β values corresponding to these limit state functions are as close as possible to a given β-value, β_{target}. The limit state functions are obtained by varying the values of α, M_S, R and N in Eq. 5 with S, D and E replaced by the expressions of (6), (7) and (8) i.e.

$$G = 1.67 \cdot \alpha^{-0.26} \cdot H^{0.44} \cdot A^{0.54} \cdot M_S - 5.36 \cdot \alpha^{-0.478} \cdot H^{0.7} - R - N \cdot A/(W \cdot F)$$

The expression for the designed door width is, using design values $x_{i,d}$ or characteristic values $x_{i,ch}$ and partial coefficients γ_i,

$$\begin{aligned} W &= \frac{N_d A/F}{1.67 \cdot \alpha_d^{-0.26} \cdot H^{0.44} \cdot A^{0.54} \cdot M_{S,d} - 5.36 \cdot \alpha_d^{-0.478} \cdot H^{0.7} - R_d} \\ &= \frac{N_{ch}\gamma_N A/F}{1.67 \cdot \alpha_{ch}^{-0.26}\gamma_\alpha^{-0.26} \cdot H^{0.44} \cdot A^{0.54} \cdot M_{S,ch}\gamma_{M_S} - 5.36 \cdot \alpha_{ch}^{-0.478}\gamma_\alpha^{-0.478} \cdot H^{0.7} - R_{ch}\gamma_R} \end{aligned} \quad (9)$$

The limit state function for the jth case is then

$$\begin{aligned} G_j(\alpha, M_S, R, N) &= 1.67 \cdot H_j^{0.44} \cdot A_j^{0.54}(\alpha^{-0.26} \cdot M_S - \frac{N}{N_d}\alpha_d^{-0.26} \cdot M_{S,d}) \\ &\quad -5.36 \cdot H_j^{0.7}(\alpha^{-0.478} - \frac{N}{N_d}\alpha_d^{-0.478}) - (R - \frac{N}{N_d}R_d) \end{aligned}$$

where H_j and A_j is room height and floor area of the building.

The element in the vector $\gamma = (\gamma_\alpha, \gamma_{M_S}, \gamma_R, \gamma_N)$ represents the ratio of the design values and some characteristic value for each parameter, e.g. $\gamma_\alpha = \alpha_d/\alpha_{ch}$. The purpose of the procedure is to derive a vector γ so that the expression

$$\sum_{j=1}^{6}(\beta_j(\gamma) - \beta_{target})^2 \tag{10}$$

is minimized where

$$\beta_j(\gamma) = \min_{\mathcal{A}} \sqrt{\Big(\frac{\alpha - \mu_\alpha}{\sigma_\alpha}\Big)^2 + \Big(\frac{M_S - \mu_{M_S}}{\sigma_{M_S}}\Big)^2 + \Big(\frac{R - \mu_R}{\sigma_R}\Big)^2 + \Big(\frac{N - \mu_N}{\sigma_N}\Big)^2} \tag{11}$$

$$= \sqrt{\Big(\frac{\alpha_j - \mu_\alpha}{\sigma_\alpha}\Big)^2 + \Big(\frac{M_{S,j} - \mu_{M_S}}{\sigma_{M_S}}\Big)^2 + \Big(\frac{R_j - \mu_R}{\sigma_R}\Big)^2 + \Big(\frac{N_j - \mu_N}{\sigma_N}\Big)^2}$$

and $\mathcal{A} = \{(\alpha, M_S, R, N);\ G_j(\alpha, M_S, R, N) \leq 0\}$.

The algorithm for deriving the vector γ can be written

1. Set the first guess of γ and characteristic values i.e. the vector of design values.
2. Solve the six values of W, (9), using the information in step 1.
3. Calculate the six reliability index β values. For a given set of limit state functions, the reliability index $\beta_j(\gamma)$ for the building condition j is obtained by measuring the distances from the points located on the limit state function "closest to" $(\mu_\alpha, \mu_{M_S}, \mu_R, \mu_N)$. Here "closest to" is measured with respect to the standard deviations $(\sigma_\alpha, \sigma_{M_S}, \sigma_R, \sigma_N)$ according to (11). This can be done by iterative methods.
4. Calculate the sum of squares using the expression (10).
5. Use an optimization algorithm that calculates the vector of design values that minimizes sum of squares of deviations.
6. The vector resulting from this procedure is the vector of design values. The partial coefficients are easily derived knowing the characteristic values for each parameter.

When expression (10) is as small as possible, then for a given limit state function, G_j, the point,

$$(\alpha_j, M_{S,j}, R_j, N_j) \tag{12}$$

is the point on the limit state function that is closest to $(\mu_\alpha, \mu_{M_S}, \mu_R, \mu_N)$. It satisfies

$$G_j(\alpha_j, M_{S,j}, R_j, N_j) = 0.$$

In general $(\alpha_j, M_{S,j}, R_j, N_j)$ is not identical to

$$(\alpha_{ch}\gamma_\alpha, M_{S,ch}\gamma_{M_S}, R_{ch}\gamma_R, N_{ch}\gamma_N) = (\alpha_d, M_{S,d}, R_d, N_d)$$

although for $j = 1, \ldots, 6$, $(\alpha_j, M_{S,j}, R_j, N_j)$ often are very close to $(\alpha_d, M_{S,d}, R_d, N_d)$.

The search for γ that minimizes (10) can for example be performed by a simplex search method. Other methods for the minimization are however possible.

OTHER OBJECTIVE FUNCTIONS

In the examples we have used the objective function $\sum_{j=1}^{6}(\beta_j(\gamma)-\beta_{target})^2$ to be minimum. Such an objective function implies that the safety level over the calculated cases are close to the specified level β_{target}. Other objective functions can be considered and may under certain circumstances be better suited. For example $\min_{j\in\{1,\ldots,6\}}(\beta_j(\gamma)-\beta_{target})_\vee$ (where $(x)_\vee = x$ if $x \geq 0$ but ∞ if $x < 0$) and $\sum_{j=1}^{6} w_j(\beta_j(\gamma)-\beta_{target})^2$ where w_j are given weights, are other objective functions. The first of these two latter alternative objective functions implies that the worst safety level of the calculated cases is close to the specified level β_{target}. The second objective function implies that buildings with heigher weights have safety level more close to the specified level β_{target}.

In general there is a non-uniqueness in γ of the minimization problem. In such a case a minimization of

$$\sum_{j=1}^{6}(\beta_j(\gamma)-\beta_{target})^2+\delta\sum_{j=1}^{6}\left(\left(\frac{\alpha_d-\alpha_j}{\sigma_\alpha}\right)^2+\left(\frac{M_{S,d}-M_{S,j}}{\sigma_{M_S}}\right)^2+\left(\frac{R_d-R_j}{\sigma_R}\right)^2+\left(\frac{N_d-N_j}{\sigma_N}\right)^2\right) \quad (13)$$

where δ is a factor specifying the relative importance of the two terms, will yield a solution close to the six points $(\alpha_j, M_{S,j}, R_j, N_j), j = 1,\ldots,6$.

APPLICATION TO A CLASS OF BUILDINGS

In this section we illustrate the concepts described so far. The results of the optimization procedure will be presented and discussed for a certain class of buildings, described by the calculation scenario.

Numerical values in the example

As mentioned earlier, the class of buildings in our example are given by the following combinations of room height H (m) and area A (m^2): (3, 1000), (5, 1000), (8, 1000), (3, 1600), (5, 1600), (8, 1600). These values correspond to quite large public buildings, e.g. different places of assembly.

Further, since β is calculated with a level 2 method, the mean and variance for each random variable in the limit state equation have to be known. In [7], the distributions for all random variables are presented and motivated; here, in Table 1, we just indicate for the variables R and α their respective mean μ and standard deviation σ. We want to emphasize that these values should be treated merely as suggestions, and that they are appropriate for the actual case of dimensions.

TABLE 1. Mean and standard deviation for the variables.

Variable	μ	σ
α (kW/s^2)	0.05	0.01
M_S	1.35	0.1
R (s)	100	80
N (m^{-2})	0.7	0.4

Note the large coefficient of variation for the variable R (behaviour and response time). Further, in [7], it has been shown, for the type of scenario in our example below, that the major contribution to the overall uncertainty comes from R.

Restriction to two random variables

As a first step, we have kept α and R as random variables in the calculations, while the other variables are treated as (deterministic) constants, equal to their respective mean values. The results are presented in the subsection below.

At an introductory stage, this may be a relevant approach. Firstly, the calculations will be faster; secondly, it is easy to visualize the results in plots. Recall from the preceding subsection that that the random variable R is important. The treatment of the case with more than two random variables is discussed below.

Results from the optimization

Now, most numerical values which are needed in the algorithm have been presented. However, a value of β_{target} in Eq. 10 must also be specified. In the following calculations, $\beta_{target} = 1.4$ was used. This value is chosen according to judgement. The value corresponds to a probability of failure of approximately 8 % (cf. (4)) given that the fire has started.

When optimization problems are to be solved, the choice of the starting point is important. The function to be minimized may have a number of *local* minima. It is therefore a good rule to compare the results obtained from different starting points. In our problem, a natural initial guess would be the expectations of the random variables, i.e. the point (μ_α, μ_R).

In Figure 2, convergence for four different starting points is displayed. The starting point is indicated by a star while the coordinate marked by a ring corresponds to the expectation of each random variable. From different starting points, the design point (α_d, R_d) is reached; in this case: (0.053, 210).

At the (overall) design point, the limit state function for each of the six design situations is plotted. The required door width in that point for each specific building is also calculated and shown in the plot. Note that these curves are not fixed because of the iterative optimization procedure; in the figure, the last position of the curves is shown. To the right in each plot the numbers W1,. . . ,W6 are the door widths (m) corresponding to the different cases (nr 1: (3, 1000), nr 2: (5, 1000), . . . , nr 6: (8, 1600)).

The final point for each of the six cases (cf. (12)) is marked by +. They appear near the design point and are hard to identify with the naked eye.

We want to point out that the design point obtained from the optimization is not situated at a distance corresponding to some β according to Hasofer-Lind. Recall that the calculations of $\beta_j(\gamma)$ in Eq. 10 are performed in a *standardized* space (cf. (11)) and are the Hasofer-Lind indices. The "outer" optimization procedure (minimization of Eq. 10) on the other hand derives values in the *original* space.

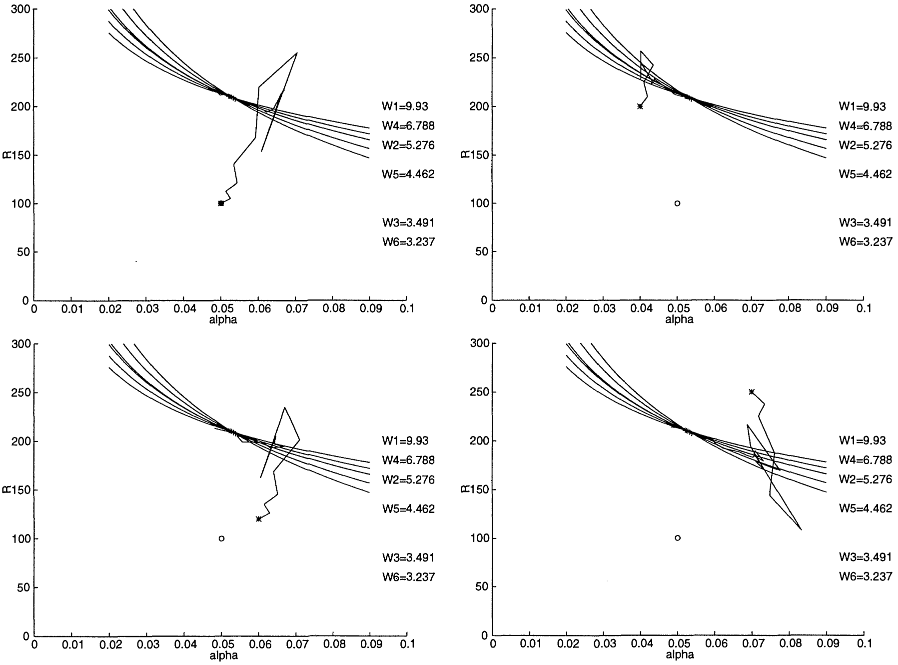

FIGURE 2: Illustration of the iterations. Starting point: $*$; Expected value: $\circ$.

Final remarks

Given the calculated design point, in the example (0.053,210), how should it be used? Values of the *partial coefficients* γ_α and γ_R can now be obtained by calculating α_d/α_{ch} and R_d/R_{ch}, where α_{ch} and R_{ch} are characteristic values. To examplify we can choose $\alpha_{ch} = \mu_\alpha$ and $R_{ch} = \mu_R$ which corresponds to the 50th percentile for symmetric distributions. This yields $\gamma_\alpha = 0.053/0.05 = 1.06$ and $\gamma_R = 210/100 = 2.10$. However if other characteristic values were chosen the corresponding value of each partial coefficient would be different. Using the design values in practice results in a safety level which is accepted i.e. meets up with the target reliability index. The design must of course be within the limits set out by the optimization work.

The given example shows the applicability of the method. It also indicates the possibility of extending the calculation to multivariate scenarios. Using different values of β_{target}, calibration procedures can be performed to derive partial safety factors which can be used as a practical design tool.

FURTHER RESEARCH

Finally, we give some remarks regarding other design situations and discuss possible extensions of the analysis.

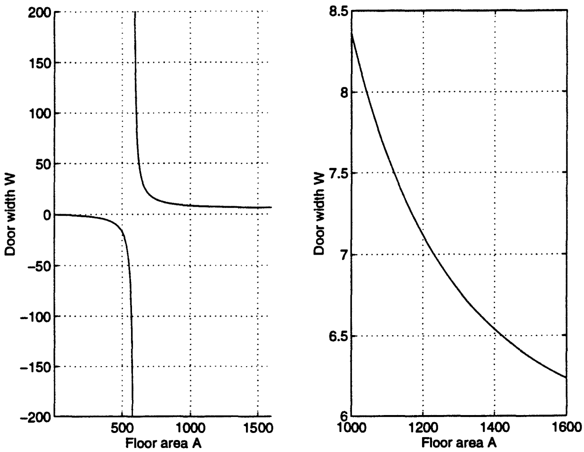

FIGURE 3: The result when we solve for W in $G = 0$ and plot W as a function of A.

More than two random variables

We have also performed calculations with four basic variables. In such a case, it goes without saying that visualizing the result will become more difficult. Another important point is that finding *one* well defined design point is usually difficult. For example, the solution of the elementary problem in $\mathbf{R}^3$ of finding the intersection between two planes may be a line; thus, it may happen that infinitely many points solve a problem.

One possibility may be to force the design point towards the minimizing points of the separate design situations. This can be done by adding an extra term in the objective function, cf. Eq. 13.

Other design situations

One can think of a case where we want to include some other design situations, e.g. smaller areas: $A = 200$, $H = 3$; $A = 200$, $H = 5$; $A = 200$, $H = 8$. In such a case, the indicated values of the expectations and variances of the random variables are not valid. From a physical point of view, this is easily understood: the awareness time is shorter in a smaller room where the fire is more easy to detect than in larger places.

Consider again the case with two random variables. If we fix some typical point (α_o, R_o), and choose some height H_o, we can calculate W as a function of A by solving the limit state equation $G = 0$. For the example shown in Figure 3 we chose $\alpha = 0.05$ kW/s^2, $R = 200$ s (values of the same order as the design point) and $H = 3$ m.

To the left in the figure, we note the two asymptotes. To the right, the region containing the areas in our example is magnified. For this choice of parameters, areas smaller than about 600 m^2 correspond to *negative* values of the door width.

We conclude that if the analysis is to be performed for other design situations, the terms in the limit state equation will have to be altered and the expectations and standard deviations must be assigned new values. An important and interesting question to be answered in a later publication is: how many subgroups (with different ranges of height and area) are needed to cover all public buildings?

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