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Theory and User's Manual for Version 1.2

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Abstract

Risk analysis tool is developed for computation of the distributions of fire model output variables. The tool, called Probabilistic Fire Simulator, combines Monte Carlo simulation and CFAST two-zone fire model. This document describes the physical models and contains a detailed user's manual. In the applications, the tool is used to estimate the failure probability of redundant cables in a cable tunnel fire, and the failure and smoke filling probabilities of electronics room during a fire of an electronics cabinet. Sensitivity of the output variables to the input variables is calculated in terms of the rank order correlations. Various steps of the simulation process, i.e. data collection, generation of the input distributions, modelling assumptions, definition of the output variables and the actual simulation, are described.

Preface

This study was carried out as a part of the Fire Safety Research project (FISRE) which is one of the projects in the Finish Research Programme on the Nuclear Power Plant Safety (FINNUS).

The study has been financed by the Finnish Centre for Radiation and Nuclear Safety, the Ministry of Trade and Industry, Fortum Engineering Ltd and Teollisuuden Voima Oy.

The theory and user's manuals are here given for the Version 1.2 of the Probabilistic Fire Simulator -software. These are the first published versions of the manuals.

Contents

THEORY AND APPLICATIONS

List of symbols

A_{fuel}	Area of the fuel surface inside the electronics cabinet
A_e	Area of the cabinet exhaust opening
A_i	Area of the cabinet inflow opening
Bi	Biot number
Fo	Fourier number
F_i	Probability distribution function of variable *i*
f_i	Probability density function of variable *i*
g_A	Limit state function
H_v	Height between the cabinet openings
h	Linearized heat transfer cofficient
k	Conductivity
n	Number of random variables
P_{A}	Probability of event A
Q	Fire load
$\dot{Q}$	Rate of heat release (RHR)
$\dot{Q}''_{fuel}$	Rate of heat release per fuel area
R_{cable}	Cable outer radius
R_{core}	Cable core radius
r	Radial position
X, **x**	Vector of random variables
x	Random variable
T	Temperature
t	Time
t_g	RHR growth time
Greek letters	
α	Thermal diffusivity
χ	Combustion efficiency
ΔH_c	Heat of combustion
ϕ_{X}	Joint probability density function
τ_d	Decay time constant of heat release rate

1. Introduction

1.1 General background

A quantitative assessment of the various effects of fire within buildings and other constructions using computational tools is a challenging mathematical problem. Buildings can be considered as systems, which respond to an external event, like fire, in a complicated way. Although the actual nature of the response may be deterministic or stochastic, the former is usually assumed for engineering applications. Time averages, or sample averages, which can be modelled in a deterministic way, yield values of design variables needed for dimensioning. Besides the building itself, there are different objects within the building that are influenced by the fire, for example people and mechanical devices. The factors influencing the response of these objects are again deterministic, probabilistic, or mixtures of both.

Presuming we had an accurate mathematical model of fire, solvable by a numerical computer code, we could, in principle, predict values of all the factors as a function of time, and let them influence the target selected for response study. Estimating uncertainty in such a system would be rather straightforward, because for a given scenario, calculating the consequences of fire is mathematically a fairly well-posed problem. The applied numerical approximations usually filter out the spatial and temporal fluctuations, caused by the stochastic nature of some phenomena. Therefore, the major uncertainty in the final results is caused by some, rather narrow uncertainty margins of the physical input variables. Both the estimation of these distributions and propagation of the implied uncertainty through the system could be calculated using standard techniques. Our experience on such systems suggests that these errors remain within a factor of two in fire scenarios needed for building design. Cases where deterministic modelling of the response is difficult or missing, are naturally exceptions.

A fire scenario is here defined as a layout of the fire scene, where a set of fire and response models is able to give deterministic values for target parameters, once the numerical inputs are given. Analogous to statistical physics, a subset of the scenario, where each of the input variables has a definite value, is called state one. This state is represented by a point in a hyperspace spanned by the input vectors. Similarly, the target is also not a unique state, but a collection of states within the scenario. To produce values needed for practical work, we have to sum up over a large number of well-defined initial and final states, system averages in terms of statistical mechanics.

Typically, the variability of system or target parameters, like the amount of fire load, is much bigger than the variability of physical input variables, like heat conductivity of a material. For this reason, they cannot be filtered out or averaged by any formal means. Usually, the system variables must be introduced in calculations through statistical distributions. Although our fire and response model is quasi-deterministic, the prediction of target response distributions requires combination of deterministic and stochastic calculation methods. A further problem, not encountered here yet, is the lack of data: there might be variables for which we do not have data either because no one has studied it or because it might be difficult to obtain. During the formulation of the problem, one must be aware of these variables because they might affect the way the uncertainty propagates through the system.

There is a lot of mathematical literature available on these problems outside fire science. Earlier works [see reviews by Hannus 1973 and Spiegel 1980] concentrated much on deterministic systems, where input variables were governed by well defined classical, like normal or lognormal distributions. Vast increase of computing power during the recent years has created interest to model large complicated systems like nuclear power plants, where the unavailability of data inevitably plays an important role. Questions of aleatory and epistemic treatment arise. A good introduction to the recent developments is given by Helton and Burmaster [1996] in an editorial to a special issue in Reliability Engineering and System Safety. Philosophical and practical aspects of the problem are discussed in special articles in the same issue [Ferson & Ginzburg 1996, Parry 1996, Paté-Cornell 1996, Theofanous 1996, Winkler 1996]. Textbook on the subject [Vose 1996] gives detailed guidance, and the application examples of Hofer *et al*. [2001, 2002] present some possible results.

1.2 Present task

Traditionally, the deterministic fire models have been used to estimate, what are the typical consequences of the fire, at the given values for the input parameters. The possible uncertainty or distribution of the input variables has been taken into account by manually varying the inputs, or carrying out classical error analysis in analytical or other formal way. The goal of this study is to develop a general tool for the probabilistic estimation of fire consequences by combining deterministic numerical simulation with tools of stochastic nature. Similar tools have been available for some time for calculations of severe accidents in NPPs, like that of Hofer *et al*. [2002]. For fire analyses, a landmark of probabilistic approach was the evaluation of partial safety factors in ref. [CIB W14, 1986]. It was a classical example of error propagation, where good deterministic models were available for the physics. More advanced methods have been reviewed recently by Magnusson [1997], but no single method has been established yet. One of the recent applications is again on nuclear sector [Haider et al. 2002]. For practical reasons, the present work is limited to those scenarios, which we believe can be modelled deterministically, and thus remain safely on the epistemic realm.

A specific task is the prediction of the failure probabilities of specified items in fires. A risk analysis model is developed using the well-known technique of Monte Carlo simulations. A commercial Monte Carlo simulation software @RISK is used for the random sampling and data processing. A two-zone model CFAST [Peacock *et al*. 1993] is used to model smoke spreading and gas temperature during the fire. The risk analysis model and the physical models are combined in a spreadsheet computing environment. The tool, called Probabilistic Fire Simulator (PFS), is intended to be fully general and applicable to any fire scenario amenable to deterministic numerical simulation. The main outcome of the new tool is the automatic generation of the distributions of the selected result variables, for example component failure time. The sensitivity of the output variables to the input variables can be calculated in terms of the rank order correlations. Sensitivity calculations are performed using plausible input data distributions to find out the most important parameters. The simulation process consists of the following steps: data collection, generation of the input distributions, modelling and assumptions, definition of the output variables and the actual Monte Carlo simulation.

Two example cases are here studied: a fire in a nuclear power plant cable tunnel and a fire in an electronics room. The cable tunnel fire was studied experimentally by Mangs & Keski-Rahkonen [1997] and theoretically by Keski-Rahkonen & Hostikka [1999]. These studies showed that CFAST two-zone model can be used to predict the thermal environment of a cable tunnel fire, at least in its early stages. Here, the effects of the tunnel geometry and fire source properties are studied by sampling the input variables randomly from the distributions. The input distributions are based on the statistics collected from the power plant.

The electronics room fire was previously studied by Eerikäinen & Huhtanen [1991]. They used computational fluid dynamics to predict the thermal environment inside the room, when one electronics cabinet is burning. The same scenario is studied here using the two-zone model. The fire source is selected randomly based on the collected distribution of different cabinet types.

2. Monte Carlo Simulation

The question set by the probabilistic safety assessment process is usually: "What is the probability that a certain component or system is lost during a fire?" This probability is a function of all possible factors that may affect on the development of the fire and the systems reaction. This question has not been dealt with exactly for fire in this form, but similar systems on the other fields have been studied extensively [Spiegel 1980, Hannus 1973, Vose 1996]. Here we adapt this general theory for our specific fire problem.

Let us denote the group of affecting variables by vector $\mathbf{X} = \left(X_1 \;\; X_2 \;\; \ldots \;\; X_n \right)^t$ and the corresponding density functions f_i and distribution functions F_i. The occurrence of the target event A is indicated by a limit state function $g_A(t,\mathbf{x})$, which is a non-increasing function of time t and vector $\mathbf{x}$ containing the values of the random variables. As an example, we define a limit state condition for a loss of component using function $g_A(t,\mathbf{x})$:

$$\begin{aligned} &g_A(t,\mathbf{x}) \leq 0, \text{if component is lost at time } t \\ &g_A(t,\mathbf{x}) > 0, \text{if component is not lost at time } t \end{aligned} \tag{1}$$

The development of fire and the response of the components under consideration are assumed to fully deterministic processes where similar initial and boundary conditions always lead to the same final condition. With this assumption the probability of event A can now be calculated by integral

$$P_A(t) = \underset{\{\mathbf{x} | g_A(t,\mathbf{x}) \leq 0\}}{\iint \cdots \int} \phi_x(\mathbf{x}) dx_i \tag{2}$$

where ϕ_x is the joint density function of variables $\mathbf{X}$. Generally variables $\mathbf{X}$ are dependent, and $\phi_x(\mathbf{x}) \neq \prod_{i=1}^{n} f_i(x_i)$.

In this work, the probability P_A is calculated using Monte Carlo simulations where input variables are sampled randomly from the distributions F_i. If $g_A(t,\mathbf{x})$ is expensive to evaluate, stratified sampling technique must be used. In Latin Hypercube sampling (LHS) the n-dimensional parameter space is divided into N^n cells [McKay *et al*. 1979]. Each random variable is sampled in fully stratified way and then these samples are attached randomly to produce *N* samples from *n* dimensional space. The advantage of this approach is that the random samples are generated from all the ranges of possible values, thus giving insight into the tails of the probability distributions. A procedure for obtaining a Latin Hypercube sample for multiple, spatially correlated variables is given by Stein [1987]. He showed that LHS will decrease the variance of the resulting integral relative to the simple random sampling whenever the sample size N is larger than the number of variables n. However, the amount of reduction increases with the degree of additivity in the random quantities on which the function being simulated depends. In fire simulations, the simulation result may often be a strongly nonlinear function of the input variables. For this reason, we can not expect that LHS would drastically decrease the variances of the probability integrals. Problems related to LHS with small sample sizes are discussed by Hofer [1999] as well as by Pebesma & Heuvelink [1999].

The sensitivity of the output y to the different input variables x is studied by calculating the Spearman's rank-order correlation coefficients (RCC). A value's "rank" is determined by its position within the min-max range of possible values for the variable. RCC is then calculated as

$$\mathrm{RCC} = 1 - \frac{6\sum d^2}{n(n^2-1)} \tag{3}$$

where d is the difference between ranks of corresponding x and y, and n is the number of data pairs. RCC is independent of the distribution of the initial variable. The significance of the RCC values should be studied with the methods of statistical testing. In case of small data sets, the actual values of RCC should be interpreted with caution due to the possible spurious correlations inside the input data [Hofer 1999].

3. Fire modelling

3.1 Smoke spreading

The transport of heat and smoke is simulated using a multi-room two-zone model CFAST [Peacock *et al*. 1993]. It assumes two uniform layers, hot and cold, in each room of the building and solves the heat and mass balance equations for each room. PFS worksheet is used to generate the input data for CFAST. The user may combine any experimental information or functions to the fire model input. The most important source term in the simulation is the rate of heat release (RHR). The RHR can be defined using analytical curves, like t^2-curve [Heskestad & Delichatsios 1977, NFPA 1985], or specific experimental curves.

Typical results of the fire simulation are gas temperatures, smoke layer position and temperature of some solid object like cable. Usually, the actual target function is the time when some event takes place. Some examples of the target functions are smoke filling time, flash over time and component failure time. In this work, the most important target function is the cable failure time. The solution of the cable heating is explained in the following section.

3.2 Cable heating

The heat transfer from the gas space to a cable is studied separately from the fire simulations and flame spread calculations. The calculation is based on the linearized model presented by Keski-Rahkonen *et al*. [1999]. Their model assumes an axially symmetric heat conduction inside a cylinder, with a radius R_{cable} and varying ambient temperature $T_\infty(t)$. Thermal properties of the cable, radius of the cable and the heat transfer coefficient must be considered random variables, as they are usually not known accuratelly.

If the metal core is omitted and homogenous insulation material is assumed, the cable insulator temperature $T(r,t)$, which is a function of radial position r and time t, can be written in an analytical form

$$T(r,t_N) = \frac{2\alpha_2}{R_{cable}^2} \sum_{i=1}^{N_\beta} \frac{\mathrm{Bi}\,\beta_i R_{cable} J_0(\beta_i r)}{\beta_i b J_0(\beta_i R_{cable}) + \mathrm{Bi}\, J_1(\beta_i R_{cable})} \Phi_i(t_N) \tag{4}$$

where α_2 is thermal diffusivity of the cable insulator material, N_β is the number of terms in the series and β_i are the roots of equation

$$J_0(\beta_i R_{cable}) - \frac{\beta_i R_{cable} J_1(\beta_i R_{cable})}{\mathrm{Bi}} = 0 \text{ , } i = 1, 2, 3, \ldots \tag{5}$$

where J_0 and J_1 are Bessel functions. Φ_i is the convolution sum of the gas temperature and exponential decay terms, as described later. Bi is the biot number

$$\mathrm{Bi} = R_{cable} h / k \tag{6}$$

where h is the linearized heat transfer coefficient at the cable surface and k is the conductivity of the insulator.

Equation (4) is relatively easy to implement, but the actual calculation is time consuming because the solution involves the roots of a non-linear equation. These roots must be recalculated to a high accuracy at each time step. For fast calculation the roots were precalculated and tabulated. The calculation method of roots β_i is explained in Appendix A. Simple and fast interpolation scheme was then used to find the approximation for the roots. The accuracy and calculation time can be controlled by selecting the number of roots (i.e. the number of terms in the solution series) to be used. Another time consuming part of the calculation is the convolution sum

$$\Phi_i(t_N) = \sum_{j=1}^{N} C_{ij} \left(A_{ij} + B_{ij} e^{-\alpha_2 \beta_i^2 \Delta t_j} \right) e^{-\alpha_2 \beta_i^2 (t_N - t_j)} \tag{7}$$

where $\Delta t_j = t_j - t_{j-1}$ and

$$A_{ij} = T_{\infty,j-1} + \left(\Delta t_j \alpha_2 \beta_i^2 - 1\right) T_{\infty,j}$$
$$B_{ij} = T_{\infty,j} - \left(\Delta t_j \alpha_2 \beta_i^2 + 1\right) T_{\infty,j-1}$$
$$C_{ij} = \frac{1}{\Delta t_j \left(\alpha_2 \beta_i^2\right)^2} \tag{8}$$

where $T_{\infty,j}$ is the ambient temperature at time t_j. If we assume that the roots β_i change slowly, and change the order of summation in (4), it can be re-arranged to form

$$T(r,t_N) = \frac{2\alpha_2}{R_{cable}^2} \left[\sum_{i=1}^{N_\beta} e^{-\alpha\beta_i^2 \Delta t_N} S_i \Phi_i(t_{N-1}) + \sum_{i=1}^{N_\beta} S_i C_{iN} \left(A_{iN} + B_{iN} e^{-\alpha\beta_i^2 \Delta t_N} \right) e^{-\alpha\beta_i^2 \Delta t_N} \right] \tag{9}$$

where S_i is defined as

$$S_i = \frac{\mathrm{Bi}\, \beta_i R_{cable} J_0(\beta_i r)}{\beta_i b J_0(\beta_i R_{cable}) + \mathrm{Bi}\, J_1(\beta_i R_{cable})} \tag{10}$$

In Equation (9), the terms of the first sum inside the brackets are the terms corresponding to the previous time steps in a recursive manner. Cable temperature at time step t_N now depends on two parts: exponentially decaying memory of the cable temperature at the previous time step t_{N-1} and the more recent effect of the gas temperature. Long convolution sums are not needed. Combined to the precalculated root tables this method was noticed to be fast enough to be applicable in Monte-Carlo simulations.

The accuracy of the analytical solutions was studied by comparing them to the results calculated with a numerical model applying finite element method (FEM). Figures 1 and 2 show the relative errors of the cable surface temperature as a function of the Fourier number Fo, in various cable configurations. The Fourier number Fo represents the dimensionless time for transient conduction [Carlslaw & Jaeger 1959]

$$\mathrm{Fo} = \frac{\alpha t}{R_{cable}^2} \tag{11}$$

The thermal boundary condition on the cable surface was a convective and radiative heat flux from a constant gas temperature 200°C. For all studied cases the magnitude of the error is acceptable, taking into account the general uncertainties related to the fire modelling.

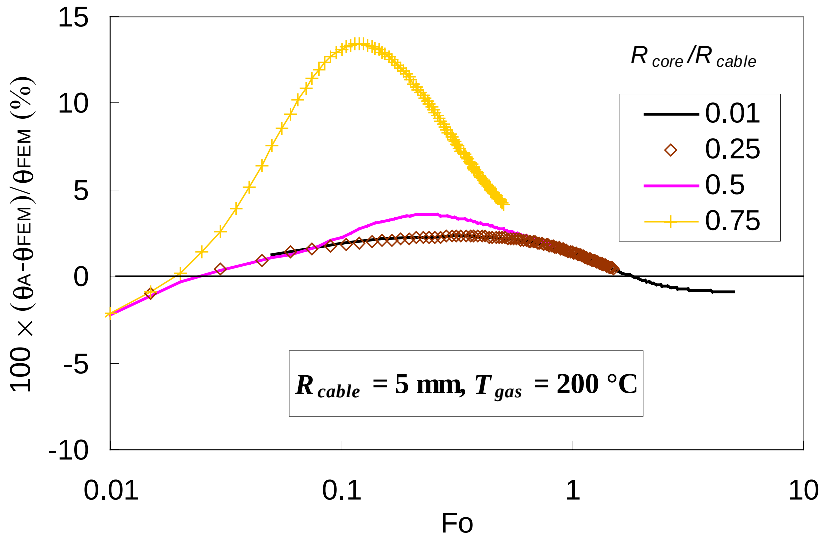

Figure 1. Relative errors of the cable surface temperature predictions of the analytical model for a 5 mm thick cable. Four curves correspond to different relative sizes of the metal core. For a fixed thermal properties and radius, the horizontal axis represents time.

The FEM models contained both the PVC insulation layer and the metal core of the cable. The analytical model in turn neglects the effect of the metal core, and assumes a homogenous cylindrical insulation material. In case of 10 mm thick cable (R_{cable} = 5 mm), shown in Figure 1, the errors are smallest when the metal core radius R_{core} is small compared to R_{cable}. For a cable with radius 30 mm, which could be a thick power cable, the results are somewhat inconsistent with the thinner case. The best accuracy is achieved with the largest R_{core}/R_{cable} -ratio, as shown in Figure 2. This inconsistency is caused by the limited number of terms in the series representation of the analytical solution.

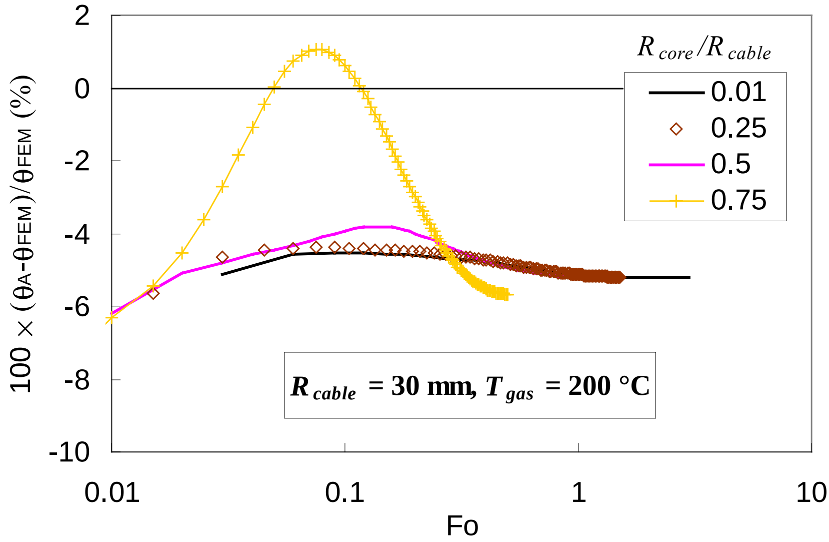

Figure 2. Relative errors of the cable surface temperature predictions of the analytical model for a 30 mm thick cable. See the explanation in the caption of Figure 1.

3.3 RHR in room fires

For a fire scenario in a compartment, rate of heat release (RHR) cannot be calculated using *ab initio* methods except for some very simple cases. If the fire load is small and fire size tiny, in relation to compartment size, fire remains local. In this simple case some theoretical methods can be applied to simple fuels, or direct calorimetric experiments for more complicated objects like electronic equipment or household utilities.

In compartments where fire size is comparable with room dimensions, or fire is likely to become oxygen limited, simple engineering methods can be derived from experimental correlations and boundary conditions. For fire growth t^2-type temporal behaviour was observed experimentally [Heskestad & Delichatsios 1977], which has already achieved a standard status [NFPA 1985]. The model is also adopted to ISO/PDTR 13387 document redefining growth factor as growth time t_g, slightly differently from NFPA 204M to fit in the metric unit of time. After flashover fire becomes oxygen limited [Drysdale 1985], and thus RHR remains roughly constant. Combining these observations to exponential decay of fire with decay time constant τ_d, we obtain a relationship, which combines maximum RHR to fire load Q and size of openings of the compartment, as well as to characteristic duration of full burning t_d [Keski-Rahkonen 1993]. Taking the integral of RHR over the whole burning time, a relation to total fire load Q is obtained

$$\int_0^\infty \dot{Q}(t)dt = \chi Q = \chi m \Delta H_c \tag{12}$$

where $\dot{Q}(t)$ is the RHR, χ is efficiency of burning, m total mass of fire load and ΔH_c heat of combustion of the material. Carrying out the integrations in closed form a polynomic relation between times is obtained

$$\left(\frac{t_1}{t_g}\right)^2 (t_d - \tfrac{2}{3} t_1 + \tau_d) = \chi Q \tag{13}$$

where t_1 is the time when maximum RHR is reached.

In a room fire scenarios, the growth time t_g and the decay time constant τ_d are found to be correlated and logarithmically normally distributed [Linkova & Keski-Rahkonen 2002, Linkova *et al*. 2003]. For unconstrained scenario

$$\tau_d = c\, t_g^n \tag{14}$$

where $c \approx 4.48$ and $n \approx 0.69$, when times as expressed in seconds. The cumulative distribution functions of τ_d and t_g are

$$F(x - x_0) = \begin{cases} \frac{1}{2}(1 - erf|z|), & x - x_0 < \beta \\ \frac{1}{2}(1 + erf|z|), & x - x_0 > \beta \end{cases} \tag{15}$$

where

$$z = \frac{\ln[(x - x_0)/\beta]}{\sqrt{2}\,\alpha} \quad \alpha > 0, \beta > 0, \quad 0 \le x_0 \le x \le \infty \tag{16}$$

For cumulative estimates, median ranks were used throughout (McCormick 1981). Fitting by inspection, the following rough estimates for the parameters were obtained; for τ_d : x_0 = 3 s, α = 1.3, and β = 221s, and for t_g : x_0 = 3 s, α = 1.15, and β = 270 s.

Fire loads are also roughly logarithmically normally distributed although Weibull and Gumbel distributions could be fitted equally well [Korpela & Keski-Rahkonen 2000].

For special scenarios RHR data may be tailored from local constraints, which may differ radically from these general trends.

4. Results and discussion

4.1 Cable tunnel fire scenario

A fire in the cable tunnel of a nuclear power plant is simulated to find out the failure probability of cables located in the same tunnel with the fire. The fire ignites in a cable tray and the fire gases heat up a redundant cable, located on the opposite side of the same tunnel. An effect of possible screen that divides the tunnel between the source and target is studied. The distribution of the heat detector activation times is also calculated. A plan view of the physical geometry and the corresponding CFAST model are outlined in Figure 3. A vertical cut of the tunnel is shown in Figure 4. The tunnel is divided in five virtual rooms to allow horizontal variations in layer properties. The fire source is located in ROOM 1 and the target cable in ROOM 3, just on the opposite side of the screen. The length of the screen does not cover the whole tunnel, and therefore it is possible that smoke flows around the screen to the target. It is also possible, that smoke flows below the screen. In the end of the tunnel is a door to the ambient. The rate of heat release (RHR) from the fire source is modelled using an analytical t^2-type curve

$$\dot{Q}(t) = \min\left\{\dot{Q}_{\max}, 1000 \cdot \left(\frac{t}{t_g}\right)^2\right\} \text{ [kW]} \tag{17}$$

where t is time, t_g is the RHR growth time and $\dot{Q}_{\max}$ is the maximum RHR, which depends on the tunnel size. t_g is treated as a normally distributed random variable with mean of 1000 s and standard deviation of 300 s. The lognormal distribution, suggested in Section 3.3, is not used because the data was not available at the time of the simulations.

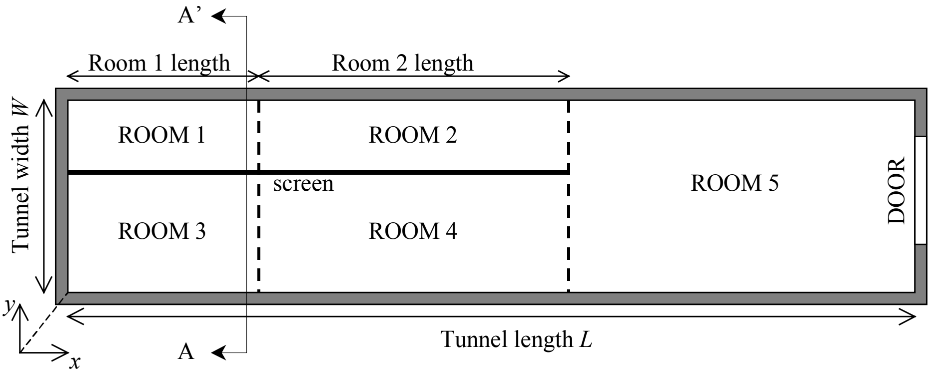

Figure 3. A plan view of the cable tunnel model.

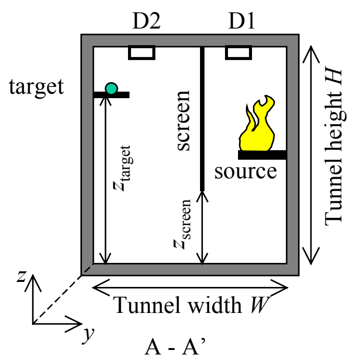

Figure 4. A vertical cut A-A' of the cable tunnel model. D1 and D2 denote heat detectors 1 and 2, respectively.

Two different versions of the scenario are studied. First, the screen is assumed to exist, with the height of the lower edge being a random variable between zero and 50 % of the tunnel height. In the second scenario, the screen is removed by setting the lower edge very close to the ceiling, retaining the virtual room structure of the model. The dimensions of the tunnel and the cable tray locations are taken from the measured distributions of the power plant. About 50 tunnel cross sections have been studied to generate the distributions. The distribution of the cable diameter is based on the measurements in seven tunnel cross sections, containing 815 cables. A complete list of the random variables is given in Table 1. While most of the variables are true physical properties and dimensions, the lengths of the virtual rooms are purely associated to the numerical model. They are treated as random variables to examine the sensitivity of the model. It is desirable that these variables are less important than the true physical variables.

Table 1. A list of random variables used in the cable tunnel fire scenario. "Measured"-text in the distribution column means that measured histograms from the true power plant are used as sampling distributions.

Variable	Distribution	Mean	Std.dev	Min	Max	Units
RHR growth time t_g	Normal	1000	300	0	3000	s
Source height z_{source}/H	Uniform			0	0.7	
Ambient temperature	Normal	20	3.0			°C
Tunnel height H	Measured					m
Tunnel width W_{tunnel}	Measured					m
Room 1 length	Uniform			2	5	m
Room 2 length	Uniform			5	10	m
Tunnel length L	Uniform			30	100	m
Door height z_{door}/H	Uniform			0.1	1.0	
Door width W_{door}/W_{tunnel}	Uniform			0.01	1.0	
Screen edge height z_{screen}/H	Uniform			0 / 0.95	0.5 / 1.0	
Dimensionless cable height z_{target}/H	Measured					
Cable radius	Measured					mm
Critical cable temperature	Normal	200	20			°C
Cable conductivity	Normal	0.16	0.05	0.1	0.5	W/Km
Cable density	Normal	1400	200	1000	2000	kg/m^3
Detector activation temperature	Normal	57	3			°C
Detector RTI	Normal	50	10	40	60	(m/s)$^{1/2}$
Ventilation time constant	Uniform			0.5	10	h
Concrete density	Uniform			1500	3000	kg/m^3

Three output variables are considered:

1. Failure time of the target cable.
2. Activation time of the first heat detector (D1), located in the room of fire origin.
3. Activation time of the second heat detector (D2), located in the room of target cable.

The Monte Carlo simulations were performed for both scenarios to generate the distributions of the output variables, and to find out the importance of each input variable. The convergence of the simulations was ensured by monitoring the values of the 10, 20, ... 90 % fractiles, mean values and standard deviations of the output variable distributions. The convergence was assumed, when the values changed less than 1.5 % in 50 iterations. About 1000 iterations were needed to reach the convergence. The simulations took typically about one day on a 1.7 GHz Pentium Xeon processor.

The distributions of the target failure times are shown in Figure 5. The overall failure probabilities can not be derived from the simulations because the distributions do not reach their final values during the total simulation time of 2400 s. However, the existence of the screen is found to dramatically decrease the failure probability of the redundant cable.

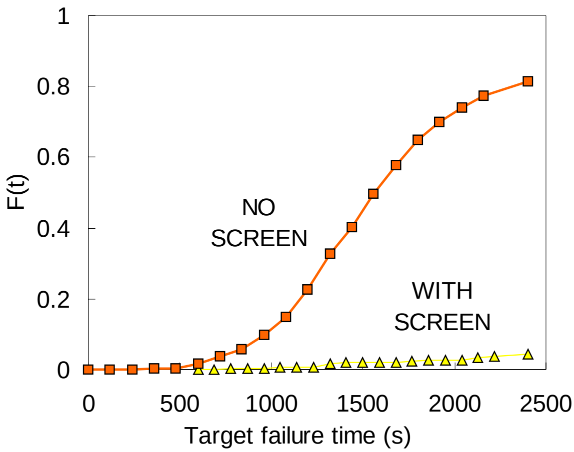

Figure 5. The distributions of the target cable failure time.

The distributions of the activation times of fire detectors D1 and D2 are shown in Figures 6 and 7, respectively. The activation time distributions of detector D1 are very narrow. For D2, the distributions are wider than for D1, and the existence of the screen decreases the activation probability from 1.0 to 0.8. The probability that the fire is detected before the target failure is studied in Figure 8 by plotting the failure times of both scenarios against the corresponding detection times. In all cases, the detection takes place before the failure.

However, this does not tell about the probability of the fire extinction because the sprinkler reliability and suppression processes are not considered.

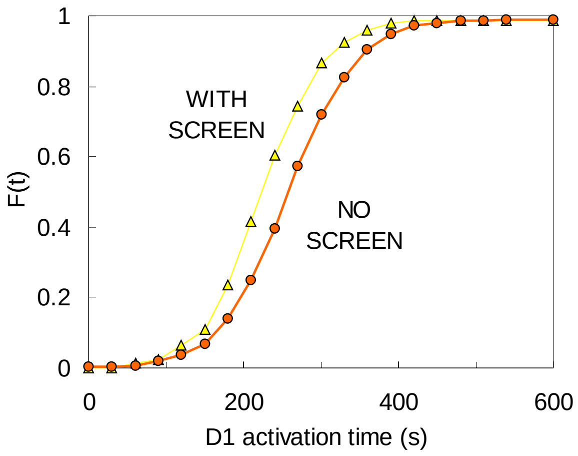

Figure 6. The distributions of the heat detector D1 activation times. D1 is located inside the fire room (ROOM 1).

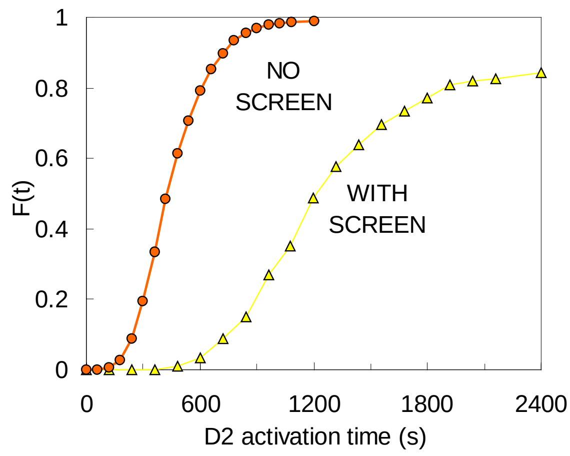

Figure 7. The distributions of the heat detector D2 activation times. D2 is located inside the target room (ROOM 3).

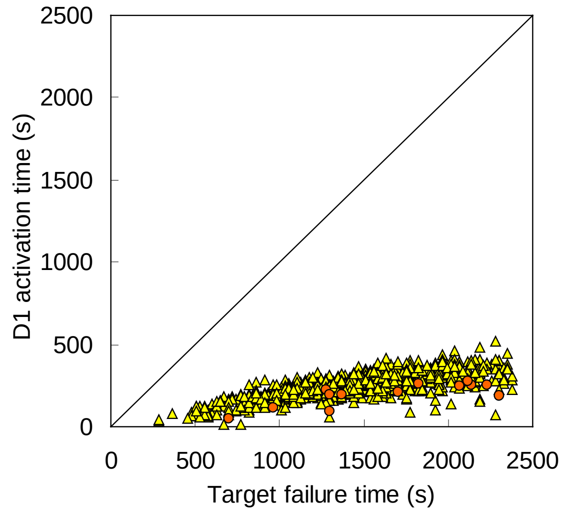

Figure 8. Comparison of D1 activation times vs. target failure times (N = 954).

The sensitivity of the target failure time for the various input variables is studied by calculating the rank order correlations. These coefficients are shown graphically in Figure 9. The two most important variables are the RHR growth time and the assumed failure temperature of the target cable. As the distributions of these two variables do not have a solid physical background, this result can be used to direct the future research. In addition, the length of the virtual fire room (room 1) has a strong correlation with the failure time. In the scenario where screen is present, the height of the lower edge of the screen has strong negative correlation with the failure time. It is therefore recommended, that the screen, when present, should reach as low as possible to prevent smoke from flowing under the screen. The rest of the correlations are not statistically significant.

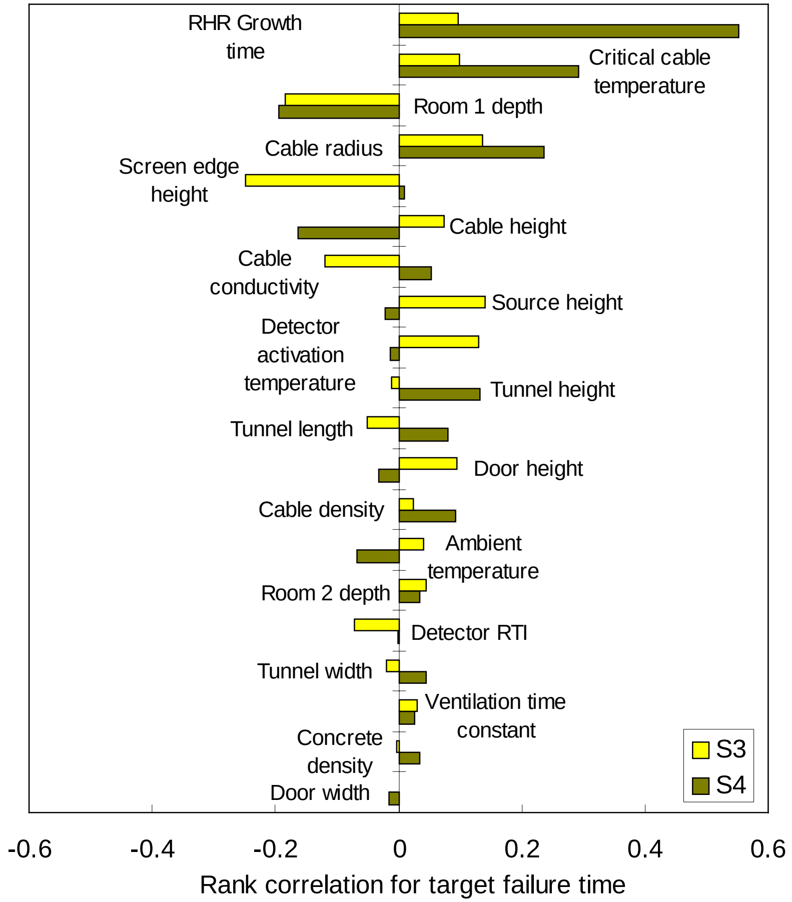

Figure 9. The sensitivity of the target failure time for the input variables. S3 = "with screen", S4 = "without screen". Here, "room depth" = "room length".

4.2 Electronics room fire scenario

As a second example, a fire of an electronics cabinet inside the electronics room is studied. In their previous study of the similar fire, Eerikäinen & Huhtanen [1991] found that a fire of a single cabinet does not cause direct threat to the other cabinets, in terms of the gas temperature in the compartment. However, it was noticed already by direct experiments [Mangs & Keski-Rahkonen 1994] the spreading of the fire and conductive heating of the components in the neighbour cabinets as well as the effect of smoke on the electronic components [Mangs & Keski-Rahkonen 2001] may cause failures in the other cabinets of the fire room. Therefore, the probability that the room is filled with smoke during a fire must be considered in addition to the temperature increase. The main target variable is the failure time of a cable inside some other electronics cabinet than the cabinet containing the fire. In addition, the convective heating of the neighbouring cabinets is not taken into account, meaning that the distance from the fire to the target is sufficiently large.

The fire room is 18.5 m long, 12.1 m wide and 3.0 m high electronics room, containing about 100 electronics cabinets in 12 rows. The room has mechanical ventilation with a constant flow rate (1.11 m^3/s) and some additional leakages to the ambient. Both the ventilation flow rate and the leakage area are taken to be random variables. Separate cooling devices and smoke circulation through the ventilation system are not taken into account, nor is the heat transfer to the room boundaries. The omission of the cooling devices is known to change the predicted gas temperature significantly. The results should therefore be considered as indicative only.

The starting point of the simulation is the collection of the physical data on the electronic cabinets. The geometrical properties and fuel content of 98 cabinets were measured. Based on the collected information, the cabinets were grouped into seven groups, shown in Table 2. The second column shows the number of cabinets in each group. P_{ign} is the probability, that the ignition takes place in the particular group, calculated based on the amount of electronic devices (circuit boards and relays) inside the cabinets. Most differences are found in the fuel surface area A_{fuel} and fire load. As these properties have an effect on the heat release rate curve, they are chosen to be distinctive properties like the vent properties.

Table 2. Grouping of the electronic cabinets. The symbols are explained in the text.

Cabinet group	Number of cabinets	P_{ign}	$H_{cabinet}$ (m)	H_v (m)	A_e (m^2)	A_i (m^2)	$\dot{Q}_{max,vent}$ (kW)	A_{fuel} (m^2)	Fire load (MJ)
HA	42	0.53	2.33	1.96	0.126	0.121	425.8	5.35	1520
2HA	9	0.18	2.36	1.97	0.129	0.110	419.5	8.54	2700
2HD	1	0.02	2.36	1.97	0.129	0.110	419.5	7.76	2000
JB	14	0.08	2.36	1.97	0.129	0.110	419.5	2.49	800
JK2	3	0.05	2.20	2.05	0.015	0.068	63.8	7.37	1200
JM	17	0.13	2.36	1.97	0.129	0.110	419.5	3.22	800
P	5	0.01	2.19	1.89	0.215	0.126	574.4	0.64	100

The rate of heat release (RHR) is calculated using a cabinet model of Keski-Rahkonen & Mangs [2003], that assumes that the heat release rate during the fully developed cabinet fire is determined by the ventilation openings in the upper and lower parts of the cabinet. The maximum RHR is given by

$$\dot{Q}_{\max,\text{vent}} = 7400\chi \sqrt{\frac{H_v}{\dfrac{2.3}{A_e^2} + \dfrac{1}{A_i^2}}} \quad [\text{kW}] \tag{18}$$

where χ is combustion efficiency factor, H_v is the height between the openings and A_e and A_i are the areas of the exhaust and inflow openings, respectively. During the fire, the cabinet doors may open due to the thermal effects. In this case, the heat release rate is not ventilation but fuel controlled, and the maximum RHR becomes

$$\dot{Q}_{\max,\text{fuel}} = \dot{Q}''_{fuel} \cdot A_{fuel} \tag{19}$$

where Q''_{fuel} is the nominal heat release rate per unit surface of fuel, a random variable in the simulation, and A_{fuel} is the free fuel area. A door opening indicator is used to select which equation is used to calculate the maximum RHR. The probability of the door-opening event during the fire is assumed 0.50. The effect of the opening time is not studied. A t^2-type RHR curve with an exponential decay rate is used. The growth and decay rates of the RHR curve are random variables in the simulation. The parameters of these distributions are taken from the experimental works of Mangs & Keski-Rahkonen [1994, 1996]. The decay phase starts when 70 % of the fire load is used.

It is very difficult to apply the zone-type fire model to the cabinet fire, because the actual source term for the room is the smoke plume flowing out of the cabinet. A reasonable representation of the smoke flow can be found if the base of the "virtual" fire source is placed close to the half of the cabinet height. Then the mass flow of free smoke plume at the height of the cabinet ceiling is roughly equal to the vent flow. Now, the height of the virtual fire source is considered as random variable. A list of the random variables is given in Table 3.

Table 3. A list of random variables used in the electronics room fire scenario.

	Distribution type	Mean	Std.dev.	Min	Max	Units
RHR growth time t_g	Uniform	750	2000	750	2000	s
Door opening indicator	Discrete			0	1	
RHR Decay time	Uniform	800	1400	800	1400	s
Cabinet type	Measured					
RHR per unit area $\dot{Q}''_{fuel}$	Normal	150	40	50	300	kW/m^2
Detector RTI	Normal	80	10	50	100	$(m/s)^{1/2}$
Detector activation temperature	Normal	57	5	40	100	°C
Critical target temperature	Normal	80	10	50	200	°C
Target radius	Uniform			1	5	mm
Leakage area	Uniform			0	3	m^2
Virtual source height $z_f/H_{cabinet}$	Uniform			0	0.5	
Ventilation flow rate	Normal	1.11	0.2	0.5	2	m^3/s

Four output variables are considered:

1. Failure time of the target cable. The cable is located 0.5 m below the height of the cabinet, therefore simulating a device inside a similar cabinet.
2. Smoke filling time: time when the smoke layer reaches the height 2.0 m.
3. Smoke filling time: time when the smoke layer reaches the height 1.5 m.
4. Smoke filling time: time when the smoke layer reaches the height 1.0 m.

The effect of the observation height is studied by observing the smoke filling at three different heights. The convergence was ensured in the same manner, as in the previous example. 700 iterations were needed for convergence at this time. The simulation took about 4 hours on a 2.0 GHz Xeon processor. The problem definition using an existing tool required a few workinghours. The data collection and analysis, in turn, took four workingdaysis, being the most time consuming part of the process. In planning and collection, the expertise of the plant personnel must be utilized as much as possible.

The distribution of the target failure times is shown Figure 10. Target failures may take place after 500 seconds, after which the failure probability increases to 0.8. Higher failure probability would be found inside the neighbouring cabinets with a direct contact to the burning cabinet, and in the ceiling jet of the fire gases. These results are inconsistent with the previous findings of Eerikäinen & Huhtanen [1991]. The most obvious reason for the different results is the longer simulation time. The overall simulated period was here 7200 s, while Eerikäinen & Huhtanen stopped their simulation soon after 600 s. At this point our failure probability is still very small. Other possible reasons for the inconsistency are the variation of the RHR curve, which may cause very severe conditions in some simulations, and the omission of the cooling devices.

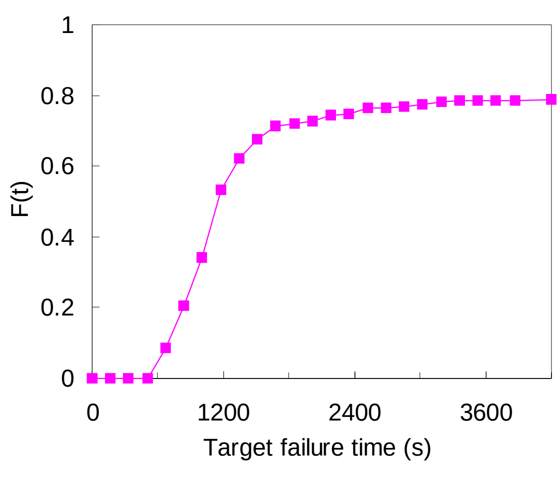

Figure 10. The distribution of the target failure time.

The distributions of the smoke filling times are shown in Figure 11. The smoke layer reaches the height of the electronic cabinets from 500 to 1800 seconds after the ignition. The overall probability of getting inside the smoke layer drops from 0.8 to 0.2, when the observation height is reduced from 2.0 m to 1.0 m.

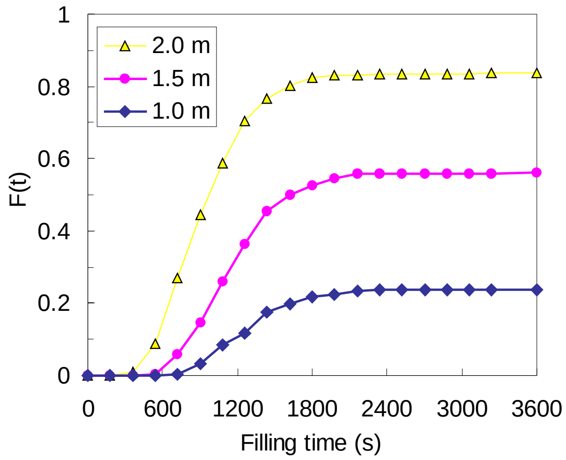

Figure 11. The distributions of the smoke filling time.

The sensitivity of the failure time to the input variables is shown in Figure 12. The height of the virtual fire source has the strongest effect on the failure time. This is very unfortunate, because in this particular application it is a numerical parameter. Other important variables are the door opening indicator, RHR growth time and the ventilation flow rate. The reliable locking of the cabinet doors is the most important physical variable that can be directly affected by engineering decisions.

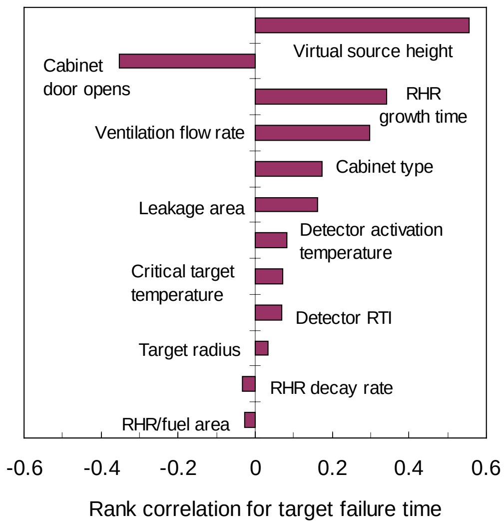

Figure 12. The sensitivity of the target failure time to the input variables.

5. Summary

Probabilistic Fire Simulator is a tool for Monte Carlo simulations of fire scenarios. The tool is implemented as a worksheet computing tool, using commercial @RISK package for Monte Carlo part. The fire is modelled using two-zone model CFAST. The Monte-Carlo simulations can provide the distributions of the output variables and their sensitivities to the input variables. Typical outputs are the times of component failure, fire detection and flashover. The tool can also be used as a worksheet interface to CFAST. Extension to the other fire models is possible.

The presented example cases demonstrate the use of the tool. Information collected from a nuclear power plant was used for the generation of the input distributions in the cable tunnel scenario, which can therefore be considered as a realistic representation of the problem. The results show that the heat detector gives an alarm before the loss of the redundant cables, with a very high probability. However, the detector reliability was not considered. According to the sensitivity measures, the most important parameters for the distribution of the failure time of the redundant cable are *i*) the growth rate of the fire, *ii*) the screen providing a physical separation of the burning and target cable trays, *iii*) the critical temperature of the cable material and *iv*) the radius (mass) of the target cable. The sensitivity information can be used to improve the safety of the redundant cables. For example, the designers can directly affect the location of the screen and placing of the different cables inside the tunnels. The distributions of the growth rate and critical temperature, in turn, are combinations of the lacking information and the range of different scenarios and materials covered in one simulation. Unfortunately, the failure time is also sensitive to the length of the virtual room of fire origin, which is a purely numerical parameter. This phenomenon should be studied more carefully in the future.

The second example considered an electronic cabinet fire inside an electronics room. The procedure of data collection, model development and actual simulation were described to demonstrate the use of the model in practical applications. The data collection and analysis was found the most time consuming part of the process. The various ways to enhance this kind of analysis are therefore needed. The simulation results showed that during a fire of a single cabinet, the thermal environment inside the room might cause a failure of an electronic component inside another cabinet, with a probability of 0.8. The inconsistency with the earlier studies can be explained with the longer simulation time and the variation of the RHR curve. Due to the strong effect of the opening of the cabinet door on the RHR curve, a reliable locking of the cabinet doors is the most important physical variable that can be directly affected by engineering decisions.

USER'S MANUAL

6. Software and hardware requirements

The Probabilistic Fire Simulator PFS is used on a personal computer having Microsoft Windows 95 or higher operating system. PFS has been implemented as a Microsoft Excel workbook. Therefore, Excel 97 or higher is needed. PFS workbook may be edited by the user, but it is the user's responsibility to save a backup copy of the original workbook.

The PFS workbook contains macros that are used to call CFAST zone model. The workbook also calls some external functions that are distributed as Dynamic Link Libraries (DLL). These files are called CableTemp.dll and CallCfast.dll. To use these DLL's one must have the Fortran type definition file dforrt.dll somewhere in the computer's path. Care should be taken that the running of the macros is enabled by the macro virus protection utility. Sometimes the calls of the external functions cause false virus alarms.

The Monte-Carlo simulations are done using commercial software @RISK[1]. Version 3.5 of @RISK or higher is needed. @RISK should always be started prior to opening the PFS workbook. If @RISK is not installed some functions of the PFS workbook do not work correctly, and must be replaced by standard Excel functions.

CFAST zone model [Peacock *et al*. 1993] is needed for the zone model simulation. Version 5.0 is recommended, because that allows running the simulations on the background. However, earlier versions may be used as well.

Any Pentium-based computer with at least 64 MB of memory and 100 MB of free disk space should be enough. However, the software has been tested on very few computers so far.

[1] @RISK is part of the DecisionTools Suite by Palisade Inc. Information on the software can be found on the company's web site: www.palisade-europe.com

7. Definitions

@RISK — The commercial Monte-Carlo simulation software that works on Microsoft Excel workbook.

detector — In the zone model, detectors are used to represent both sprinklers and actual fire detectors.

distribution function

The statistical distribution used for sampling of a random variable. The distribution functions are provided by @RISK. During the Monte-Carlo simulation, these functions return a random value but during the interactive use, they return the mean value of the distribution.

interactive use

The PFS workbook can be used simply as an interface for the available fire models. It provides a simple and fast method to use CFAST zone model, for example. @RISK is not needed during the interactive use.

output variable

A variable whose value or the distribution of values is the results of the simulation. A typical output is a time, when some condition is met. For example, target failure time, detection time of the fire or time to flashover.

sampling — A mathematical algorithm that picks one value randomly from a given distribution.

target — Target is a physical object whose temperature is calculated during the fire, and whose failure time is examined. The original purpose of PFS was to study the distribution of the failure time of the redundant cables in cable tunnel fire. This was done by calculating the temperature of the target cable shield and assuming some critical temperature, for example 200 °C. User may add other types of targets than just cables. A target has some thermal properties and a physical size and location. All of these properties may be random variables.

thermal database

A collection of material properties like material thickness and conductivity needed by CFAST. If any of the material properties is a random variable, the database must be generated during every iteration of the Monte-Carlo simulation.

8. Using Probabilistic Fire Simulator

8.1 General

The Probabilistic Fire Simulator (PFS) is implemented as Microsoft Excel workbook. The individual calculation operations are grouped on worksheets. For example, the worksheet FireSource contains the analytical formulas and experimental data that are used to define the rate of heat release (RHR). CableTemperature worksheet in turn is used to combine the results from several possible models available for the calculation of the cable temperature.

Although the spreadsheet program updates all the worksheets almost instantaneously every time some data has been changed, it is useful to define the order in which the data are used, as a logical way to proceed through the definition of the simulation data and the actual simulation. In the following sections, separate procedures will be presented for the use of PFS as a user interface for the fire model and the Monte-Carlo simulations. The procedures correspond to the PFS workbook in the form as it is distributed. Every user may, and is even encouraged to, modify the workbook, in order take the full advantage of the flexibility of PFS.

8.2 Fire model user interface

The PFS workbook can be used as an interface for the CFAST fire model independently of the Monte-Carlo feature. It is even possible to use the workbook without @RISK software, but some changes are then needed to avoid the Excel -error messages due to the missing @RISK functions. If @RISK is not installed, replace the distribution functions (RiskNormal, RiskUniform, RiskGeneral etc.) on RandomVariables worksheet with the values of the corresponding variables. Also, replace the CurrentIter() function on the Control worksheet by zero.

The suggested order of the steps needed to do a single simulation is shown as a flowchart in Figure 13. The actual order of the definition steps is not always crucial, but the geometry definition is recommended before the other issues, because the geometry sets some natural limitations for the locations of targets and detectors.

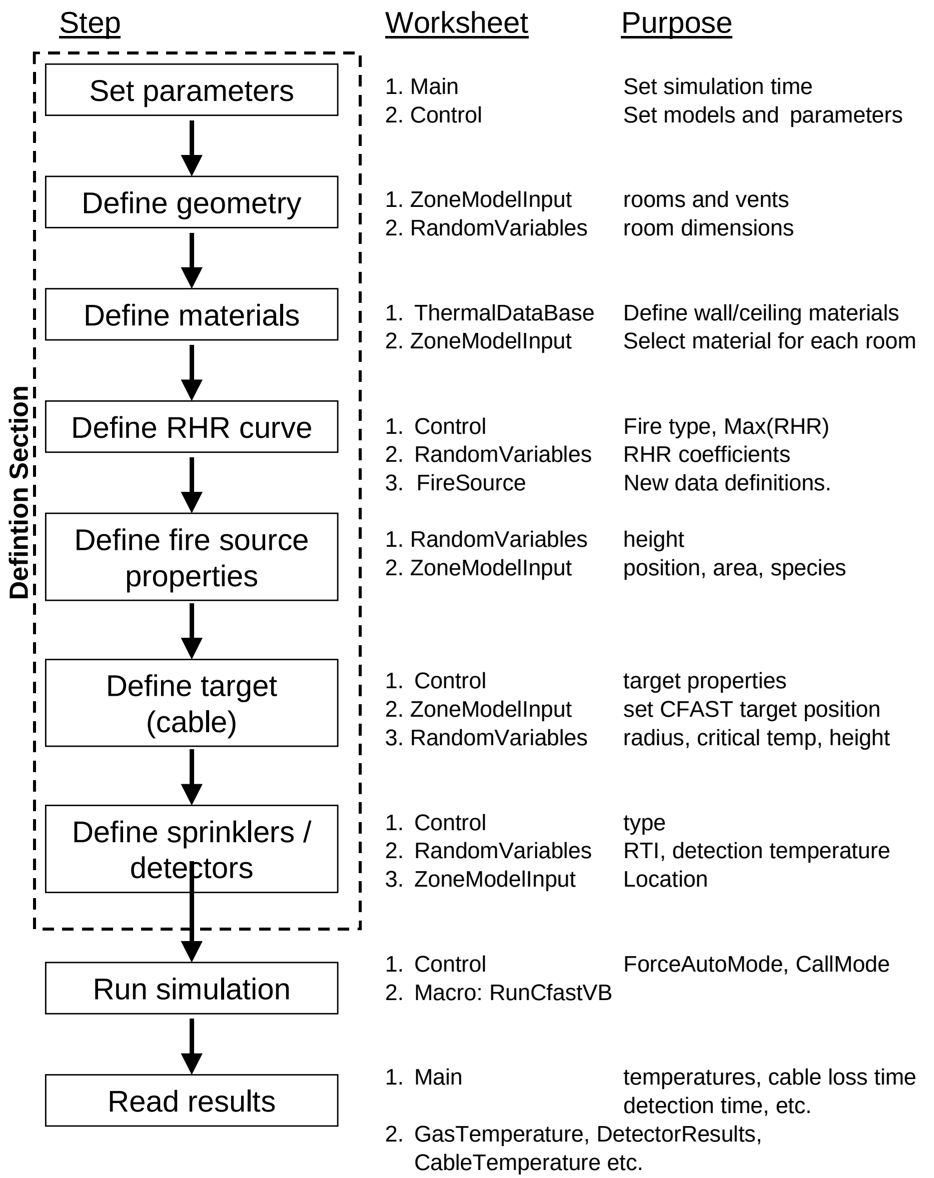

Figure 13. Suggested order of the steps needed to define the input data and to do a single fire simulation using PFS.

8.2.1 Set parameters

The basic parameters are the total simulation time, found out the Main worksheet, and the various control parameters, found on the Control worksheet. The control parameters are used to select the physical models for heat release rate and the calculation of gas and target temperatures. The rooms where the layer temperatures and heights are reported are selected on the ZoneModelInput worksheet, under the TARGET ROOMS keyword.

8.2.2 Define geometry

This step is done by defining the room dimensions, vent dimensions and the vent opening / closing times. The room dimensions can be set by a number of different ways on the RandomVariables and ZoneModelInput worksheets. Values on the other sheets are usually linked to the value on the RandomVariables sheet. During the interactive use, the distribution function returns the mean value, and is therefore transparent to the user. As an alternative, the sampling can be done from general, measured distributions.

Two vents can be defined between each room. The vent properties are all defined on ZoneModelInput worksheet, under the HVENT keyword. The opening and closing times can be defined under the CVENT keyword for the first vent only. The possible second vent is assumed always open. It is also possible to set the breaking temperature for window glasses T_w. The corresponding vent is then opened, if the upper layer temperature $T_{up} > T_w$, and the layer interface is below the window softit, on either side of the window. CFAST, itself, can not handle breaking windows, but PFS interface will make several runs and open the vents as the breaking condition is met. However, the comparison of layer interface and window soffit heights requires that the rooms are on the same level, ie. HI/F -values are equal.

Mechanical ventilation can be modelled by defining fans between the rooms. The connection points (nodes) and fan properties are all defined on ZoneModelInput worksheet, under the MVOPN and MVFAN keywords, respectively. Each node must have a room where it is located and orientation. The flow-pressure curve of the fan is modelled using a constant value. The number of fans must be less than seven. The fans are typically used to define mechanical smoke ventilation system. The second room is then set to the ambient. Actually, CFAST allows the modelling of a complete ventilation network with fans and nodes, but here only the fans are used to keep the interface simple.

8.2.3 Define materials

If the ceiling and wall materials are varied, or the heated target is modelled using CFAST target utility, the thermal database should be generated for every simulation. The following steps are needed to use this functionality:

1. On the Control worksheet, under *CFAST control* section, set CreateThDb variable TRUE. By default this variable should be FALSE, because the writing of the thermal database file slightly slows the Monte-Carlo simulation. The thermal properties are then read from the file defined on ZoneModelInput worksheet that must exist in the CFAST directory.

2. The material properties are defined on the ThermalDataBase worksheet. First, the number of used materials is set. It should be between 1 and 20. Use only as many materials as you need to minimise the size of the thermal database file. The target material, for example PVC, is usually defined on the first row of the database. The material properties can be connected to random variables, sampled at the RandomVariables worksheet.

3. The building materials are selected on the ZoneModelInput worksheet. The name of the existing database file should be given without the file name extension .df. The wall and ceiling materials are selected under the CEILI and WALLS keywords with the number of corresponding material in the thermal database. If all the cells are left blank, all the ceilings (or walls) are assumed adiabatic. On the other hand, if any of the cells has a value, the blank cells (or walls) will have the properties of concrete.

8.2.4 Define RHR curve

To define the rate of heat release (RHR) curve it is necessary to define the fire type and maximum value of RHR. The maximum value is needed for the analytical RHR curves to prevent the unphysical situations. The fire type is selected at the Control worksheet. The fire types, the data source and possible parameters are listed in Table 4. Type 1 is the typical design fire with t^2-type growth [Heskestad & Delichatsios 1977, NFPA 1985], and an exponential decay [Keski-Rahkonen 1993].

For special scenarios RHR data may be taylored from local constraints, which may differ radically from these general trends. The actual RHR data is stored on the FireSource worksheet. This is the place to add new RHR curves.

Table 4. Fire types and the corresponding parameters defined in PFS.

Index	Type	Parameter
0	Constant RHR	RHR
1	t^2-type $\dot{Q}(t) = \min\left[\dot{Q}_{\max}, 10^3 \cdot (t/t_g)^2, 10^3 \cdot \exp(-(t-t_d)/\tau_d)\right]$, where t_g is the growth time, t_d is the decay start time and τ_d is the decay time constant, [Keski-Rahkonen 1993, Linkova & Keski-Rahkonen 2002, Linkova *et al*. 2003].	t_g, t_d, τ_d
2	Fire area grows at constant flame front velocity v_{fl}.	v_{fl}
4	Experimental RHR of horizontal cable trays, measured by Mangs & Keski-Rahkonen [1997].	
101-114	Experimental RHR curves of household appliances, measured by Hietaniemi *et al*. [2001] 101-104 Dish washers 105-107 Washing machines 108-111 Refridgerator-freezers 112-114 TV sets	
201-205	Experimental RHR curves of smoke detector test fires, measured by Björkman & Keski-Rahkonen [1997] 201 TF1, open cellulosic fire 202 TF2, smouldering wood 203 TF3, glowing cotton 204 SPVC 205 FPVC	

301-306	Experimental RHR curves of electronic cabinets, measured by Mangs & Keski-Rahkonen [1994]. Experiments 1, 2C, 3, 4, 5 and 6B

8.2.5 Define fire source properties

Besides the RHR curve, the fire source has the following properties: position, area, compartment of origin and the species yields. The height of the fire source can be controlled from the RandomVariables worksheet, as it one of the most important properties. Other properties are defined on the bottom of the ZoneModelInput worksheet.

The yields of two species can be given. By default they are OD (soot) and CO. One value is given for both species, and the value is kept constant trough the fire. The calculation of the ceiling jet flows is controlled by the CEILI keyword. Usually it can be given a value "ALL". The fire area is assumed linearly proportional to the RHR with maximum value defined at the "Maximum Fire Area" cell. However, this variable has usually very small effect to the simulation results. A detailed description of the parameters is given in the CFAST manual.

8.2.6 Define target

The properties of the target, for example cable, are mainly controlled at RandomVariables and Control worksheets. To summarise, some of the target properties (radius, critical temperature and relative height) are shown on the Main worksheet, while most of the properties are defined on the Control worksheet.

The first parameter of the Target temperature –section at the Control worksheet is the model index. The following models are available at the moment:

Index	Target temperature model
0	Time constant. Cable temperature follows gas temperature with a time constant depending on the cable size and thermal properties. This model has shortest possible calculation time, but it is accurate only for very thin cables.

1 Analytical cable model. The cable shield temperature is calculated based on the analytical solution of the axisymmetric heat transfer equation. Also quite fast, but the accuracy is not guaranteed.

2 CFAST/Target The heating of the target can be modelled using the CFAST target utility, which allows the heat transfer calculation of 1D heat transfer inside the zone model. This method is very useful, as it allows the contribution of the radiative heat transfer, which is very difficult to calculate outside the zone model. The target material is selected at ZoneModelInput worksheet by typing the index of the corresponding material in the thermal database to the "Material #" column, under the TARGET keyword. Usually the first material of the thermal database is reserved for targets. The heating of the axisymmetric objects, like cables, can be approximated by setting the material thickness to $R/(2\pi)$, where R is the cable radius.

3 FEM. The most accurate solution to the cable heat transfer equation can be obtained by 1D Finite Element Method (FEM), including both the insulator shield and the metal core of the cable. The gas temperature is used for the boundary condition on the cable surface.

4 FEM/target. This method is an experimental version. The FEM method is used to solve the cable heat transfer, but the boundary condition is taken from the target boundary heat flux given by CFAST. The model should not be used.

The results given by the methods 1 to 4 are compared in Figure 14, showing the failure time distributions for some t^2-type fire and relatively thin cable. It can be seen that the analytical model and FEM give very similar distributions, but CFAST target gives clearly smaller failure times. This is probably due to the radiative heating. The FEM/target option is shown to give very different results, and are considered wrong.

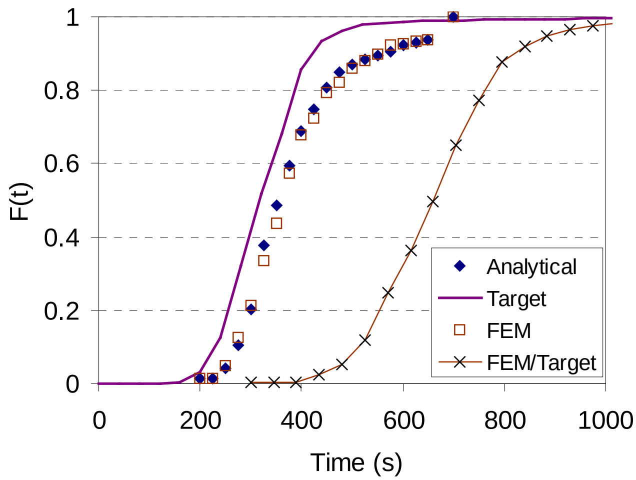

Figure 14. Comparison of the different target (cable) heating models.

8.2.7 Define sprinklers and detectors

The modelling of the heat detectors is a well-established procedure, and the reliability of the detection time predictions can be considered reliable. The modelling of the smoke detectors is still under active research, and this utility should be used with caution. Heat detectors represent both sprinklers and actual heat detectors.

The detector parameters are summarised on the Main worksheet. These parameters include detector type (1 for smoke, 2 for heat), operation temperature and RTI. As the modelling of the smoke detectors is developed further, it will be possible to add delay parameters of the Weibull distribution describing the distribution of penetration delays. Usually these parameters depend on the detector type and flow velocity. Detector location, consisting of the room number and physical co-ordinates, are defined on ZoneModelInput worksheet, under the keyword DETECT. All the variables can be linked to random variable distributions at RandomVariables worksheet.

8.2.8 Run simulation

First, set the simulation and CFAST parameters on the Control worksheet. These parameters are mainly used for debugging purposes. By setting "ForceAutoMode"–variable to 1 user may force the CFAST to run every time the workbook is updated. The default is 0. DTCHECK-parameters at the "CFAST control" section control the critical time step size of CFAST solver. "CallMode" parater controls whether the temporary files are deleted after CFAST simulation or not. Normally (value 0) all the files are deleted, but in the debug mode (value 1) left on the hard disk.

The actual simulation is started by running a macro RunCfastVB. It can be found under the Tools/Macro –menu of Excel.

8.2.9 Read results

The simulation results (time series) are organised to various worksheets, depending of the type of the data. For example, gas temperature data are found at the GasTemperature worksheet, detector data at the DetectorResults worksheet and cable temperature at the CableTemperature worksheet. Some scalar values, like the target failure times are calculated as table lookups at the "Main" worksheet. All the data read from the CFAST results are found at CallCfast worksheet. Most of the results are shown as time series. One exception is the detector operation times, which are reported in the cells just above the corresponding detector temperature time series.

8.3 Monte-Carlo simulation

The suggested order of the steps needed to carry out a Monte-Carlo simulation is shown as a flowchart in Figure 15. The purpose and means of the individual steps are described below.

8.3.1 Start @RISK

The first step of the Monte-Carlo simulation use of PFS, is to start @RISK software. See the @RISK manual for details. @RISK automatically starts Microsoft Excel, enabling the statistical functions and opening two custom toolbars. These toolbars can be used to define @RISK inputs and outputs, open @RISK simulation settings panel, and to open other Decision Tools –software applications.

8.3.2 Open PFS workbook

PFS is implemented as a Microsoft Excel workbook. To start a new simulation project, open an existing workbook, and save it with a new name. **Always keep a backup copy of the original workbook!**

8.3.3 Definition section

The definition of the fire scenario and the selection of the physical models follow the steps shown in the definition section of Figure 15.

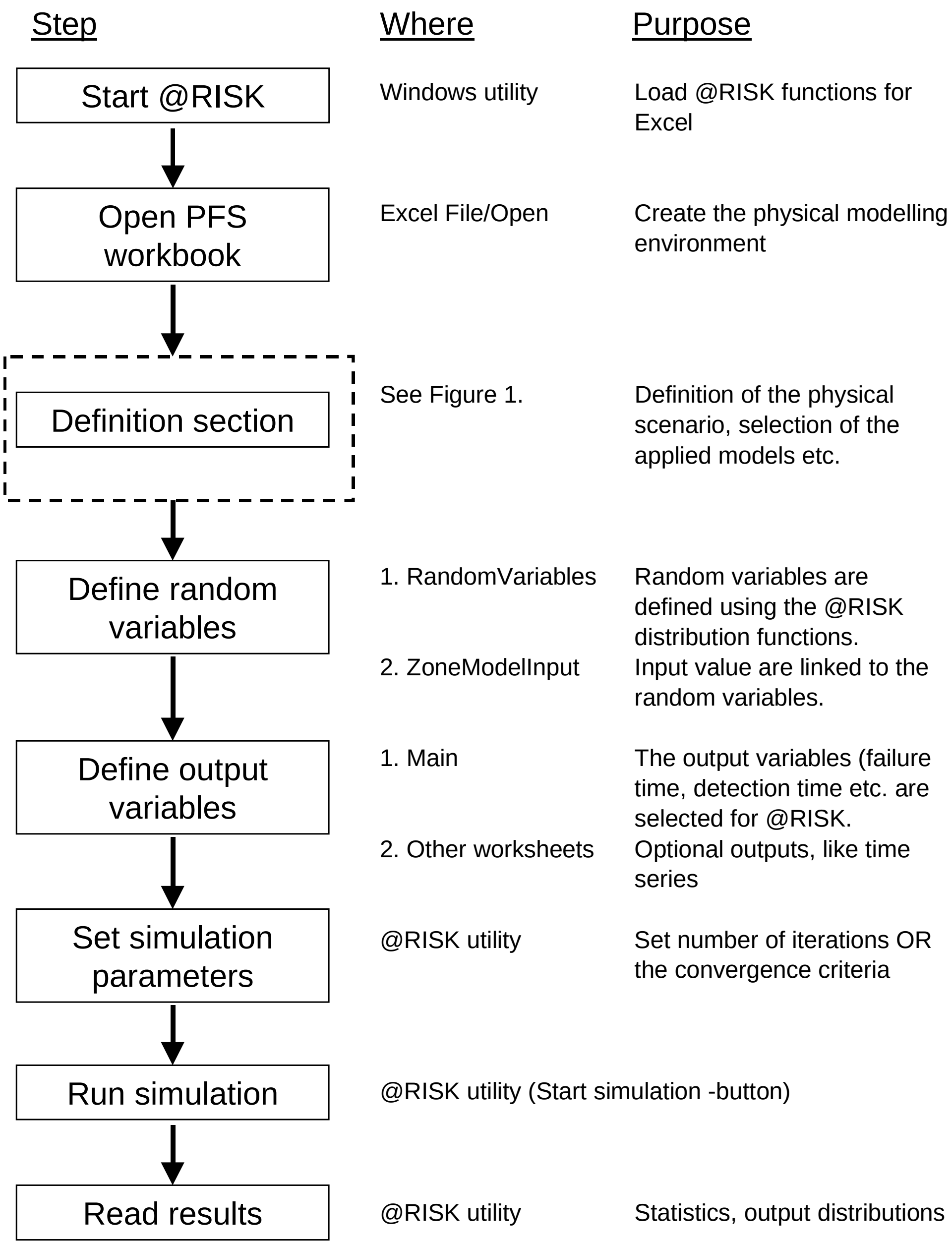

Figure 15. Suggested order of steps needed to do Monte-Carlo simulation with PFS.

8.3.4 Define random variables

The definition of the random variables is what makes the fire simulation of a Monte-Carlo simulation. In practice it means that the value of some physical variable is calculated by @RISK as a sample from some statistical distribution. During the interactive use of the workbook, the distribution function returns the mean value of the distribution. The distribution functions are defined on the RandomVariables worksheet.

Some examples of the statistical distribution functions, that are available in @Risk 3.5, are listed in Table 5. See @RISK documentation for other distributions. The corresponding worksheet functions, used in Excel, have a prefix "Risk". Possible functions are, for example, RiskNormal(6.2,2.0) and RiskUniform(0,1). In practice, the distribution parameters are linked to the other cells of the PFS workbook.

Table 5. Examples of the statistical distribution functions available in @RISK 3.5.

Function	Returns
CUMUL(minimum,maximum, {X1,X2,...,Xn},{p1,p2,...,pn})	cumulative distribution with n points between minimum and maximum with cumulative probability p at each point
DISCRETE({X1,X2,...,Xn}, {p1,p2,...,pn})	discrete distribution with n possible outcomes with the value X and probability weight p for each outcome
LOGNORM(mean,standard deviation)	lognormal distribution with specified mean and standard deviation
NORMAL(mean,standard deviation)	normal distribution using mean and standard deviation
TNORMAL(mean,std.deviation, minimum,maximum)	normal distribution truncated at minimum and maximum
UNIFORM(minimum,maximum)	uniform distribution between minimum and maximum
WEIBULL(alpha,beta)	weibull distribution with shape parameter alpha and scale parameter beta

8.3.5 Define output variables

To collect the statistics of the interesting output variables, they must be defined as @RISK outputs, by selecting the corresponding cell, and pressing the "Output" -button of the @RISK toolbar. Typical outputs are the failure time of the target(s) and detector activation time. It is possible to define a time series, like gas temperature, as output.

8.3.6 Set simulation parameters

The parameters of the Monte-Carlo simulation are set on the @RISK simulation settings panel, opened by pressing the "Change @RISK settings" button in the @RISK toolbar. The following parameters are usually set:

Iterations tab:	# Iterations = 300. This setting has no effect, if the auto-stop feature is used (recommended).
	Update display. **This setting must be selected when using CFAST or other external model!** Otherwise, the output variables are not saved.
Sampling tab:	The sampling type = Latin Hypercube. However, Monte-Carlo sampling should be used if there are defined correlations between the input variables.
	Standard Recalc = Mean value.
Convergence tab:	Monitor convergence should be selected, and checking frequency set to 50 (smallest possible value).
	Auto-Stop should be selected, with a convergence criterion of 1.5 %. This ensures that the Monte-Carlo iterations are continued until the output statistics are well converged.

8.3.7 Run simulation

The Monte-Carlo simulation is started by pressing the "Run simulation" button of the @RISK toolbar.

During the simulation, the CFAST-console is opened on the screen, typically hundreds of times (if CFAST -fire model is used). This makes it practically impossible to use the computer for any interactive work during the simulation.

8.3.8 Read results

The output statistics are studied by opening the @RISK main window. Press "Open @RISK Main Window" -button in the @RISK toolbar.

For each output variable, @RISK reports the mean value, standard deviation and several fractiles. The graphical output can be used to plot the distribution of the output variable. The graphs can be exported to a separate Excel workbook.

9. Input variables and parameters

This section describes the purpose of the input variables and parameters found on each worksheet. Some guidance on the use of these parameters is also given.

9.1 Main

The Main worksheet contains only one input variable: MAXIMUM TIME, which is the maximum simulation time (s) in all the simulations. It should be set approximately equal to the maximum expected value of the output variables. If too short, the tail of the time distribution can not be calculated. If too long, the resolution of the time series becomes poor (resolution = maximum time / 100).

Some of the most important input parameters are summarised on the worksheet to provide a simple way to check their values. The actual distributions are defined elsewhere in the workbook.

9.2 Control

The Control worksheet contains a number of parameters that are used to choose between various physical models and fire sources, set numerical parameters or target properties. The parameters are organised to the following groups:

Fire

Type	Selects the fire source type. These types are listed in Table 4.
RHR Limiter	Upper limit of the rate of heat release (kW). This parameter is used to define the constant phase of the RHR curve. It is also used to avoid unphysical RHR values, that could slow the execution of the zone model.
RHR/fuel area	Rate of heat release per fuel surface area ($kW.m^{-2}$). This parameter is used, if the RHR curve is defined by

	flame spread velocity (type 2).
Gas temperature	
Model	Selects the fire model. 0 = constant gas temperature, 1 = Alpert's ceiling jet model, 3 = CFAST.
Constant	Constant gas temperature (°C), used if Model = 0.
Sprinkler/Detector Control	
Type	Type of the fire detectors: 1 = smoke detector and 2 = heat detector. For smoke detectors, the detector temperature follows the corresponding ceiling jet temperature exactly. This models the operation of a detector with RTI = 0, and having no thermal inertia.
Sprinkler	A flag that is used to set the water flux on after the detection. If 0, the detector does not try to suppress the fire. This is the suggested choise, because the suppression feature of CFAST does not work correctly, so far.
Target temperature	
Model	Selects the heat transfer model for the target temperature calculation. 0 = time constant (lag), 1 = analytical cable model, 2 = CFAST target, 3 = FEM with gas temperature boundary condition, 4 = FEM with CFAST target heat flux boundary condition (not recommended).
General	
Initial temperature	Initial target temperature (°C).
Heat transfer coeff.	Convective heat transfer coefficient ($W.K^{-1}m^{-2}$) of the target cable.
Insulation properties	
Emissivity	Cable surface emissivity.
Conductivity	Thermal conductivity of the cable insulation material

	($W.K^{-1}m^{-1}$).
Density	Density of the cable insulation material (kg m^{-3}).
Specific heat	Specific heat of the insulation material ($J.kg^{-1}K^{-1}$).
Core properties	
Radius	Radius of the cable core (m).
Conductivity	Thermal conductivity of the cable core material ($W.K^{-1}m^{-1}$).
Density	Density of the cable core material ($kg.m^{-3}$).
Specific heat	Specific heat of the cable core material ($J.kg^{-1}K^{-1}$).
Parameters of the analytical model	
Niter	Number of iterations. Typically from 1 to 3. Larger the number, more time it takes.
Nroots	Number of terms (roots) used in the series. Can be 1, 3 10 or 30.
CFAST control	
DTCHECK	Time step size control parameter for CFAST. Does not seem to work properly in CFAST 4.1. That is, CFAST does not stop if the time step is smaller than xval for longer than nsteps.
CallMode	0 for normal use, 1 for debug purposes. In debug mode, the temporary files are not deleted from the CFAST directory.
ThDbCreate	Flag to control the use of thermal database. If TRUE, thermal database is written on every iteration. Must be set TRUE, if any of the thermal properties is random variable.
Simulation control	
Force Auto Mode	Used for debug purposes. If set to 1, CFAST is automatically called every time, the workbook is updated, ie. any of the cells is changed.

9.3 Random Variables

The RandomVariables worksheet contains the actual distribution functions. By default, 20 independent variables can be defined. The function definitions should be located in the "Input" -column. The parameters of the distribution are collected on the same worksheet. In case of dimensionless random variables, the actual dimensional variable can be calculated in the right most column. It is the user's responsibility to link the zone model input variables and target properties to the cells of the "Input" -column.

Below are listed some variables that are often defined on this worksheet:

Ambient temperature	Distribution of the ambient temperature (°C).
Cable Radius	Distribution of the cable radius (mm).
Critical cable temperature	Distribution of the critical surface temperature (°C), where the target is lost.
Detection penetration parameter	Distribution of the time lag parameter (s), used in the statistical detector model.
Detector activation temperature	Distribution of the operation temperature of the fire detector (°C). For heat detector, this is the true operation temperature. For smoke detectors, no well-established value exists.
Detector RTI	Distribution of the response time index of the detector ($\sqrt{m/s}$).
Relative cable height	Distribution of the relative (dimensionless) target height, defined as z_{target}/H.
Relative source height	Distribution of the relative (dimensionless) height of the fire source, defined as z_{fire}/H.
RHR Decay rate	Distribution of the decay rate τ_d.
RHR Decay start	Distribution of the starting point t_d of the decay period of the t^2-type RHR curve.
RHR Growth time	Distribution of the growth time parameter t_g (s), used in the t^2-type RHR curves. This parameter can

	serve in other purposes too, depending on the selected fire source type.
ROOM DEPTH	Depth of the fire room (m). In tunnel geometry, this is the length of the tunnel. It should be at least four times the room width.
ROOM HEIGHT	Height of the fire room (m). General room height distribution can be used.
ROOM WIDTH	Width of the fire room (m). General room width distribution can be used instead of analytical distributions.

9.4 Zone Model Input

This worksheet contains data that is specific to the zone models, especially CFAST. To understand the way that the data are organised, user should be familiar with the format of the CFAST input files.

Most of the data on this worksheet is already defined elsewhere in the PFS workbook. It is the user's responsibility to link the cells to the random distributions or other input sections.

TARGET ROOMS	These numbers determine the rooms where the layer heights and the zone temperatures are reported.
NROOMS	Number of rooms in the model.
DAT file	The name of the CFAST input file.
HI file	The name of the CFAST history file.
Thermal DB	The name of the CFAST thermal database file, without the ".db" extension.
Maximum Run Time	This parameter is used to limit the CFAST execution time, to stop simulation in cases where

	CFAST solver has locked itself to the very still equations. Cfast is stopped after the given number of seconds. It should be large enough, that the slowest of the normal simulations can be executed. The default is 600 s.
TIMES	Print = interval of text output Display = interval of graphical output Only one of these intervals should be greater than zero. History determines the temporal accuracy of the results. Usually 1 s is used, but it can be made smaller to reduce the size of the history file.
TAMB	Ambient conditions inside the structure.
EAMB	Ambient conditions outside the structure.
HI/F	Height of the floor for each room (m).
WIDTH, DEPTH, HEIGH	The dimensions of the rooms (m).
CEILI	This index determines the ceiling material for each room. The integer number should correspond to the material numbers of the thermal database. If left blank, gypsum properties are used. If all the cells of the row are blank, ceilings are considered adiabatic.
WALLS	This index determines the wall material for each room. The integer number should correspond to the material numbers of the thermal database. If left blank, gypsum properties are used. If all the cells of the row are blank, walls are considered adiabatic.

HVENT

The vents between the rooms are defined as connection matrices, under keyword HVENT. Two vents can be defined between each room. Actually, CFAST can handle four, but the limit of two was accepted to keep the PFS interface simple. The first vent is defined by defining the vent dimensions in the upper triangle of the connection matrix, and second vent in the lower. If the cell is blank in all three matrices, the vent does not exist.

Width	The vent width (m).
Soffit	The height of the vent soffit (upper frame) measured from the first room floor.
Sill	The height of the vent sill (lower frame) measured from the first room floor.

CVENT

The first vent can be opened and closed once during the simulation. The opening time should be given in the upper triangle of the CVENT matrix, and closing time in the lower triangle. If the both cells are blank, the corresponding vent is always open. The element should correspond to the elements of the HVENT matrices. The second vent is always open.

As an alternative, the vent can be defined to be opened when the window breaking condition is met ($T_{up} > T_w$ and $Z_i <$ soffit height). To use breaking condition, set the opening time of the vent to a negative number. The breaking temperature is set above the CVENT matrix. The default value is 200 ºC.

TARGETS

NTargets	The number of targets in the simulation. NTargets should be an integer, from 0 to 3.
Room #	The index of the room, where the target is located.
X (m)	The x-coordinate of the target (m). (Corresponds to the depth of the room.)

Y (m)	The y-coordinate of the target (m). (Corresponds to the width of the room.)
Z (m)	The z-coordinate (height from the floor) of the target (m).
Normal X Normal Y Normal Z	The components of the target surface normal vector (m).
Material #	The target material determined as an index to the thermal database.

DETECTORS

NDetectors	Number of detectors in the simulation. Integer from 0 to 6.
Type	1 for smoke detector, 2 for heat detector
Room #	The index of the room, where the detector is located.
T_{activ} (K)	Activation temperature (°C).
X (m)	The x-coordinate of the detector (m). (Corresponds to the depth of the room.)
Y (m)	The y-coordinate of the detector (m). (Corresponds to the width of the room.)
Z (m)	The z-coordinate (height from the floor) of the detector (m).
RTI	The response time index of the detector ($\sqrt{m/s}$).
Sprinkler	0 for detector only, 1 for sprinkler.
Spray density	The water spray density of the sprinkler (m/s).

FANS

Nfans	Number of fans in the simulation. Integer from 0 to 6.
1st room	The index of the upstream room.

Orientation	1 for horizontal orientation (typical for ceiling openings), 2 for vertical orientation
Height	The vertical height of the node, from the 1st room floor level (m).
2nd room	The index of the downstream room.
Orientation	The orientation of the second node.
Height	The vertical height of the node, from the 2nd room floor level (m).
Area	The opening area of the nodes.
Pmin	The minimum pressure, under which the flow is constant (Pa).
Pmax	The maximum pressure, over which the flow goes to zero (Pa).
Flow	The constant flow rate (m^3s^{-1}).

CHEMI

Molar weight	The weight of the fuel molecule in amu (C = 12).
Humidity	The relative humidity of the atmosphere (%).
LOI	The limiting oxygen index of the fuel. This is the smallest oxygen concentration (%) where the combustion can take place.
$-\Delta H_c$	The heat of combustion for the fuel ($J\ kg^{-1}$).
T(fuel,init)	The initial fuel temperature (K).
T(ign, gas)	The ignition temperature of the gaseous fuel (K).
Radiative fraction	The radiative fraction of the rate of heat release. Usually about 0.3.
LFBO	Index of the compartment of fire origin.
FPOS	The co-ordinates of the fire inside the compartment. X corresponds to depth, Y to width and Z to height.

CJET	String that determines which ceiling jets are to be calculated. Usually CJET should be ALL.
Maximum fire area	The maximum area of the fire (m^2). The time dependent area is proportional to RHR.

SPECIES

It is possible to define the yield of two species. Actually, CFAST can handle seven, but the limit of two was accepted to keep the PFS interface simple. The possible species are HCN, HCL, HCR, CT, O2, OD (optical density = soot) and CO. The species are selected by writing the corresponding strings under the keywords Specie1 and Specie2. The yields are assumed to constant in time, and therefore only the first value is given.

9.5 Distributions

It is possible to use general distributions for the sampling of the random variables. Distributions worksheet is reserved for the definition of these distributions. The general distribution is defined as a set of value-probability pairs.

9.6 Thermal Database

Thermal database consists of up to 20 rows of material data. The number of materials is defined first. The number of materials should be kept as small as possible to minimise the execution time. For some reason (which is still unknown) CFAST does not accept the last material of the database. **Consequently, the last row of the database should not be used!**

Each row of the material database contains the following data. At the moment, the material can only have one layer, although CFAST can handle up to 3 layers. A description of the material can be written on the right side of the material data table.

Name	The material name should be a string of up to 8 characters.
Conductivity (W/Km), Specific heat (J/kgK), Density (kg/m3)	The thermal properties.
Thickness	The thickness of the material layer (m).
Emissivity	Surface emissivity.
Coefficients of HCL deposition	

10. Modifying PFS

10.1 PFS Workbook

The workbook has two major modes: Interactive use and non-interactive use. Interactive use means the case where user sets the input variables and explicitly runs the CFAST calling routine CallCfastVB. Non-interactive use means the Monte-Carlo simulation. The mode is detected on the Control workbook, under Simulation Control. CurrentIter() is a @RISK function returning the iteration number. If zero, we are using PFS interactively, and the ControlInterActiveMode variable is set to TRUE.

To find out if the CFAST can be called, the code must check the status of the random distribution page. This is done by computing a sum of the random variables, and referring to that sum in the equation of the ControlDoFunCall variable on the Control worksheet. Consequently, ControlDoFunCall is set to TRUE, if that sum has been updated (all the variables have been sampled] and the ControlInteractiveMode is FALSE.

The actual CFAST calling is done on the CallCfast worksheet. The columns from AN to BV form a variable CfastResArray, which is written by the CallCfastVB subroutine. In ControlDoFunCall variable is TRUE, the same result is written to columns BX - DF, by the CallCfastFun function. Finally, the data is collected to the first columns B - AL.

Another point, where direct function calls are used is the CableTemperature worksheet. There the CableTempPL function is called to calculate the temperature rise of the axisymmetric cable. The function is located in the CableTemp.dll and all the input data is passed as arguments.

The array functions are typed by painting the array, typing the formula, and pressing Ctrl+Shift+Enter.

10.2 Visual Basic functions and subroutines

The PFS workbook contains the following Visual Basic functions and subroutines:

FirstLookup	A simple lookup function which interpolates the lookup result between the data points. Not used at the moment.
CallCfastFun	A function that calls a Fortran function CallCfastFun (in CallCFast.dll), which then actually calls CFAST. CallCfastFun has no arguments. In case of breaking windows, the function has a loop that calls WriteCfastDataFun and CallCfast functions until all the windows have broken or remained closed.
CallCfastVB	A subroutine that only calls CallCfastFun and writes the result to the worksheet. This is needed because the functions are not directly available for interactive calling.
WriteCfastDataVB	A subroutine that provides an interactive access to the WriteCfastDataFun function.
WriteCfastDataFun	A non-interactive function that reads input data from the workbook and then send the data to the Fortran function WriteCfastData (in CallCfast.dll). The arguments are the OverRideCVENT flag, and CVENTIN array. They are used to update the vent opening time array CVENT during the calling loop.

MatrixCopy This subroutine is used to copy a two dimensional array.

10.3 Fortran functions

The actual data writing, CFAST calling and the reading of the results is done by Fortran functions. These functions are normally provided as dynamic link libraries (DLL). The source code of the functions can be provided if needed. However, these functions should be modified only by an advanced user, because the passing of the arguments between Visual Basic and Fortran, or Excel and Fortran, is very complicated.

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Appendix A: Computation of the roots β_i for the cable heat transfer equation

Using the Hankel's asymptotic expansion of Bessel functions [Abramowitz & Stegun 1965] valid for large argument x » 0

$$J_\nu(x) = \sqrt{2/\pi x}\left\{P(\nu,x)\cos\chi - Q(\nu,x)\sin\chi\right\} \tag{A}$$

where P and Q are power series of inverse x, and

$$\chi = x - (\nu + \tfrac{1}{2})\tfrac{\pi}{2} \tag{B}$$

it can be shown that the roots of equation

$$J_0(x_n) - x_n J_1(x_n)/\mathrm{Bi} = 0 \tag{C}$$

for large n can be calculated from

$$x_n = (n - \tfrac{3}{4})\pi + \delta_n \tag{D}$$

where

$$\delta_{n,i+1} = \overline{\arctan}\left\{\frac{P(0,x_{n,i}) - Bi\,x_{n,i}\,Q(1,x_{n,i})}{Q(0,x_{n,i}) + Bi\,x_{n,i}\,P(1,x_{n,i})}\right\} \tag{E}$$

The functions within the braces are rational functions of inverse x, and therefore the ratio behaves very regularly for large x. Iteration of a few rounds of i between Equations (D) and (E) will lead to solution of roots at high accuracy.

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Abstract

Risk analysis tool is developed for computation of the distributions of fire model output variables. The tool, called Probabilistic Fire Simulator, combines Monte Carlo simulation and CFAST two-zone fire model. This document describes the physical models and contains a detailed user's manual. In the applications, the tool is used to estimate the failure probability of redundant cables in a cable tunnel fire, and the failure and smoke filling probabilities of electronics room during a fire of an electronics cabinet. Sensitivity of the output variables to the input variables is calculated in terms of the rank order correlations. Various steps of the simulation process, i.e. data collection, generation of the input distributions, modelling assumptions, definition of the output variables and the actual simulation, are described.

Keywords
fire prevention, fire safety, simulation, simulators, user manual, risk analysis, computation, calculations, models, estimation

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