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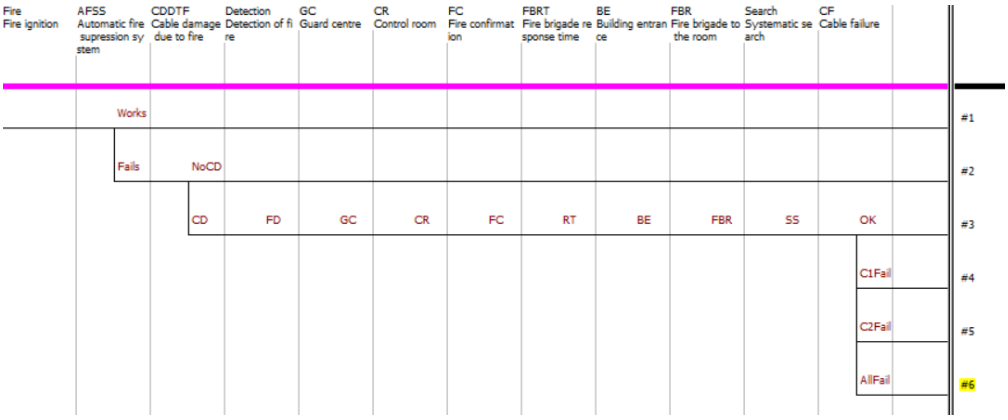

Extensions to cable room fire PRA study and method

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Confidentiality:	VTT Public

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Summary

This report continues the probabilistic fire risk analysis study on nuclear power plant cable room fire. The scenario has been modelled using a simulation-based event tree in FinPSA software. The main components of the model are Monte Carlo fire simulations and a stochastic operation time model for firefighting. In this report, the dependencies between fire brigade actions and fire progression are explored further.

A large number of uncertainties are identified for the case study. The most significant uncertainties are related to some fire simulation parameters (particularly time of maximum heat release rate), reliability of the automatic suppression system and some central firefighting actions.

Reliability analysis of sprinkler systems is studied by reviewing previous analyses found in the literature and conducting a simplified fault tree analysis for a generic wet pipe system. Such reliability analyses have been quite rare or at least not published. Collection of sufficient amount of failure data for sprinkler system components is necessary for credible reliability analysis.

Some new modelling issues are considered from the point of view of simulation-based event tree modelling. Modelling of multiple consequences, such as multiple cable failures, is relatively straightforward as demonstrated by a simple modelling example. Multiple fire brigades could also well be incorporated to the operation time model given that sufficient information about time delays exist.

Confidentiality	VTT Public

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Preface

This report is the deliverable of the task ‘Fire PRA’ (T1.2) of the project of ‘New Development and applications of PRA’ (NAPRA) on 2020.

The goal of NAPRA T1.2 is to apply simulation-based event trees to model fire scenarios in order to make fire PRA more realistic. This report presents the results of the year 2020.

The project is part of SAFIR2022 research programme, funded by VYR. The work was supported by TVO, which provided some information related to sprinkler systems.

Espoo 15.12.2020

Authors

Contents

1. Introduction

Deterministic fire hazard analyses, investigations of the operating experience at nuclear installations and fire probabilistic risk analysis (PRA) (OECD 2015) have demonstrated that knowledge of the frequency of the occurrence of fires is an important contributor to nuclear power plant (NPP) fire risk assessment. However, fires and associated plant responses are complex phenomena, and therefore the estimates of fire risk are subject to considerable uncertainty. Fire PRA has often been characterized as being less mature and less realistic than other internal events PRA. Perceptions of immaturity can affect stakeholders' use of fire PRA information. Unrealistic fire PRA results could affect fire-safety related decisions and improperly skew comparisons of risk contributions from different hazards (Siu & Sancaktar 2015). Modelling the firefighting defence-in-depth including human actions can be used to reduce conservatism by taking into account the possibility of preventing the damages of critical components and failures of safety functions in a fire situation. Attempts of this kind of an approach have earlier been made by e.g. (Hostikka et al. 2012a), (Kloos et al. 2014) and (Sakurahara et al. 2018), but practicality of the method still needs further development.

One of the main limitations of the generally used fire PRA methodology is that it is not capable of adequately accounting for the dynamic behaviour and effects of fire due to its reliance on the classical PRA methodology i.e. event trees and fault trees (Sakurahara et al. 2014). In this study, simulation-based event trees of FinPSA software (Tyrväinen et al. 2016; VTT 2020) are used to model a cable room fire scenario. The aim is to develop an approach for more realistic fire PRA. Simulation-based event trees are particularly useful to model impacts of time delays and dynamic dependencies, such as how the time available for fire brigade to arrive depends on the progression of the fire itself, which contains significant uncertainties.

This report continues the work presented in (Tyrväinen et al. 2020). In (Tyrväinen et al. 2020), the NPP cable room fire analysis scenario from (Hostikka et al. 2012a) was implemented in a simulation-based event tree of FinPSA. The main components of the model are Monte Carlo fire simulations and a stochastic operation time model for firefighting. The fire simulations were performed separately using deterministic Fire Dynamics Simulator (FDS) (McGrattan et al. 2013), and the results of the simulations were imported to FinPSA. The so-called "stochastic operation time model" was implemented in FinPSA scripts in eight parts corresponding to different operational phases, including fire detection, guard centre actions, control room actions and fire brigade actions.

The objectives of this work are:

- to explore more dependencies between the fire brigade actions and fire progression.
- to identify uncertainties related to the cable room fire analysis.
- to study the reliability of the automatic suppression system.
- to consider other fire scenarios in order to extend the modelling approach.

2. Simulation-based event trees

PRA software FinPSA (VTT 2020) includes a module for simulation-based event trees. The module has been developed for probabilistic analysis of severe nuclear reactor accidents (Tyrväinen et al. 2016, Tyrväinen & Karanta 2019), but it is, in practise, a general-purpose probabilistic risk analysis tool. The module combines event trees with computation scripts written using FinPSA's own programming language, so-called "containment event tree language" (CETL). In the script files, the user defines functions that calculate probabilities of event tree branches and possibly other variable values, such as amounts of consequences or timings of events. The script files enable the use of various different modelling approaches, because contents of the scripts are not limited in any way, except that they must conform to the CETL syntax.

The model includes a separate script file for each event tree section, for an initial section, and for a common section, which is common to all event trees in the project if there are multiple event trees. A function name is assigned to each event tree branch, and the function has to be defined in the script file of the corresponding event tree section. The function returns the probability of the event tree branch. It is also possible to write other functions that are called e.g. by branch functions. The model can include both global variables and local variables limited for a specific event tree section. Normal variable types, such as ‘real’, ‘integer’, ‘Boolean’ and ‘string’, can be used. Distributions of few different types can also be specified. A set of built-in functions is available, including some distribution operations.

To account for uncertainties related to variable values, it is possible to specify probability distributions for parameters and perform Monte Carlo simulations. At each simulation cycle, a value is sampled from each specified distribution, and based on that, numerical conditional probabilities are calculated for all event tree branches. Values are calculated for all variables at each end point of the event tree. After the simulations, statistical analyses are performed automatically to calculate frequency and variable value distributions for each end point among other statistical results and correlation analyses. It is also possible just to calculate point values of the event tree based on the mean values of distributions. Event tree sequences can also be grouped by a binner routine, and combined results can be calculated for the specified consequence categories.

3. Cable fire case study

3.1 The original case study

The NPP cable room fire case study presented here was originally presented in (Hostikka et al. 2012a). The analysed cable room contains both power and I&C cables of two redundant subsystems (B and D). The cables of the subsystems are physically separated in a multi-level metallic cable tray system. In the places where the cables of different subsystems are close to each other, mechanical shield plates have been installed between the cable trays. The cables are the primary fire load in the room, and the power cables are the most probable source of ignition. In this study, the ignition is assumed to occur in the power cables of subsystem B, and the analysis aims to estimate the probability of cable failure in subsystem D.

The original analysis was performed using PFS, i.e. Probabilistic Fire Simulator (Hostikka & Keski-Rahkonen 2003; Hostikka 2008), and FDS, i.e. Fire Dynamics Simulator (McGrattan et al. 2013). PFS is an Excel tool that uses VisualBasic macros and dll libraries. PFS generated the simulation cases using Latin hypercube sampling based on given random variables, created the input files for FDS, managed the simulation runs and performed the post-processing of simulation results automatically. The random variables included the location of the initial fire, the size of the initial fire, properties of power cables and concrete, and the response of the sprinkler system (if working). PFS also performed stochastic operation time simulations of firefighting operations. For each simulation point, it was checked whether the fire brigade was able to suppress the fire before the cable damage. In addition, it was checked whether the firefighting conditions were tolerable when the fire brigade arrived to the room. The stochastic operation time simulations were performed using random number sampling functions of Excel.

3.2 Operation time model

The time delays of the operation time model were related to fire detection, control room operations and fire brigade operations. The simulation model includes eight phases:

1. Detection

   There is a delay between the ignition and the detection. Detection can take place through smoke detectors and an automatic alarm system, sprinklers, or through the human senses.

2. Alarm

   The information about the detection is transmitted to the security centre and the control room of the NPP as well as to the Emergency Response Centre. The fire brigade receives the information via an alarm system and by phone.

3. Fire brigade response

   After the alarm the fire brigade leaves the fire station and moves to the destination.

4. Fire brigade clearance to the building entrance

   The first assessment of the situation, the unit manager's instructions, and the transition to the front door.

5. Fire brigade arrival at the room of origin of fire

   Finding the destination, moving there and pressurizing the hoses.

6. Co-operation with the plant personnel

   Collaboration is needed between the fire department and the control room. Fire brigade will check the situation and possibly ask for voltage cut-off in the room of origin.

7. (Possibly) Voltage cut-off for the safety of the fire brigade using water-based suppression

   The operator performs the necessary actions from the control room.

8. Systematic search

   Systematic search with thermal imaging. Extinguish the fire when it is found.

Most of the phases consist of multiple actions, and the model includes possible additional time delays caused by human errors and equipment failures. The operational actions are illustrated in Figure 1. After the fire is detected, the control room calls the guard centre, which alarms the fire brigade. There are parallel actions related to control room personnel and arrival of the fire brigade. The control room sends a person to confirm that there is a fire. When the fire brigade arrives, the control room and the fire brigade need to co-operate, and the control room personnel may need to cut-off the voltage before the fire brigade can enter the room and suppress the fire.

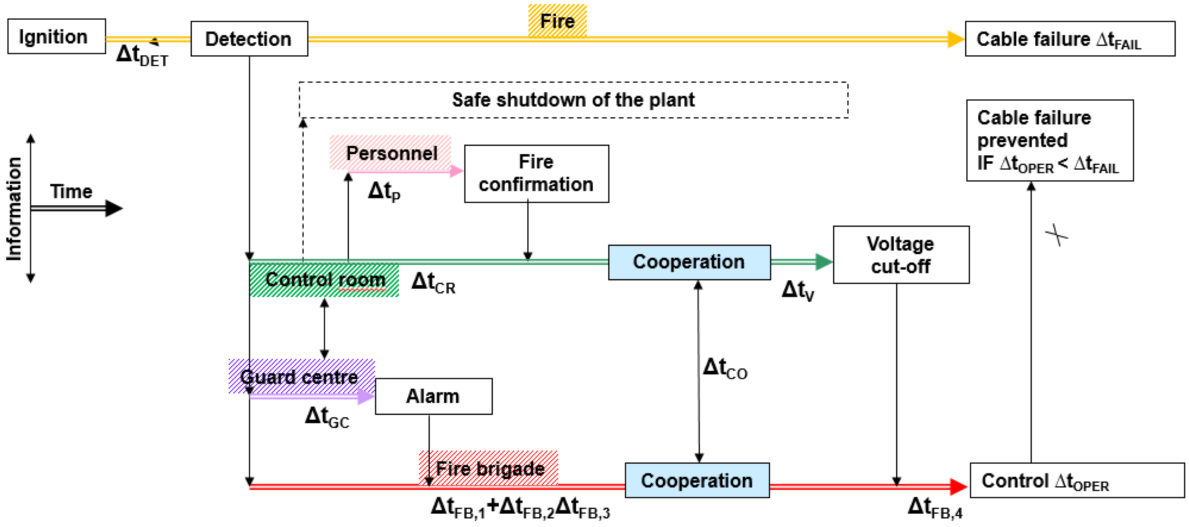

Figure 1: The operational actions related to firefighting (Hostikka et al. 2012a).

The total operation time delay from the ignition to the suppression is calculated as

$$\Delta t_{OPER} = \Delta t_{DET} + \max\left[\Delta t_{CR}, \left(\Delta t_{GC} + \Delta t_{FB,1} + \Delta t_{FB,2} + \Delta t_{FB,3}\right)\right] + \Delta t_{CO} + \Delta t_{V} + \Delta t_{FB,4},$$

where Δt_{DET} is the delay from the ignition to the detection, Δt_{CR} is the time it takes for the control room to confirm the fire and perform other preparations before co-operating with the fire brigade, Δt_{GC} is the time it takes for the guard centre to alarm the fire brigade, $\Delta t_{FB,1}$ is the fire brigade response time, $\Delta t_{FB,2}$ is the fire brigade clearing time to the building entrance, $\Delta t_{FB,3}$ is the travel time from the building entrance to the room where the fire is located, Δt_{CO} is the delay related to the co-operation between the fire brigade and the control room, Δt_{V} is the time it takes to cut-off the voltage, and $\Delta t_{FB,4}$ is the time it takes to find and extinguish the fire.

The details of the stochastic operation time model are presented in (Hostikka et al. 2012a), (Kling 2010) and (Tyrväinen et al. 2020).

3.3 Simulation-based event tree model

In (Tyrväinen et al. 2020), the case study was implemented in a simulation-based event tree of FinPSA. The event tree model is presented in *Figure 2*. The fire simulation results from FDS were imported to FinPSA scripts as vectors. Values of three variables were imported: the detection time, cable damage time and time when the firefighting conditions become intolerable. The operation time model was implemented in FinPSA scripts completely in eight sections according to the operation phases.

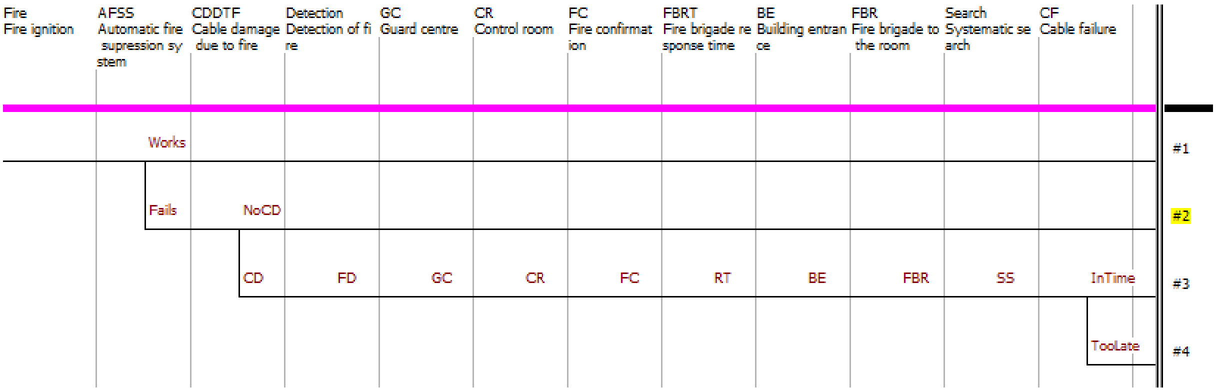

Figure 2: Event tree with operation time model.

The details of the model are presented in (Tyrväinen et al. 2020). As an example, the scripts related to the guard centre are the following:

```
real p_anf, p_wa, r_anf, r_wa, r_wi, t_mca, t_cud, t_wa

routine init
  p_anf = raneven(0.01,0.05)  $ Auto-notification failure probability
  p_wa = raneven(0.01,0.05)   $ Probability of wrong address
  p_wi = raneven(0.01,0.05)   $ Probability of wrong interpretation of the alarm

  t_mca = raneven(0.1,0.5)    $ Making a collective alarm
  t_cud = raneven(1,1.5)      $ Calling the unit director
  t_wa = raneven(2,10)        $ Wrong address
  t_aso = raneven(0.5,5)      $ Alarm set-off
  t_wi = raneven(1,10)        $ Wrong interpretation of the alarm
  t_cgc = raneven(0.5,2)      $ Call to the guard centre

  r_anf = random()
  r_wa = random()
  r_wi = random()
return


function nil GC
  $ Guard centre operation time is determined
  t_gc = t_mca+t_cud

  if r_anf < p_anf then
  begin
    t_gc = t_gc+t_aso+t_cgc
    if r_wi < p_wi then t_gc = t_gc+t_wi
  end

  if r_wa < p_wa then t_gc = t_gc+t_wa
return nil
```

In the final section of the event tree, the operation time from the detection to the beginning of the systematic search is calculated. Then, for each fire simulation cycle, it is checked whether the cable failure occurs before the suppression, and whether the room conditions are such that the fire brigade can enter the room when they are ready. In other words, for each fire simulation, it is determined whether the fire brigade is in time or not. The probability of a cable failure is calculated based on the number of simulation cycles where the fire brigade was too late.

4. Dependencies between the fire brigade actions and fire progression

The original case study was performed using Probabilistic Fire Simulator (PFS) (Hostikka & Keski-Rahkonen 2003; Hostikka 2008), which managed the Monte Carlo fire simulation. PFS generated the simulation cases using Latin hypercube sampling based on given random variables, created the input files for FDS, managed the simulation runs and performed the post-processing of simulation results automatically. The random variables included the location of the initial fire, the size of the initial fire, properties of power cables and concrete, and the response of the sprinkler system (if working). Also the dependencies of the target outcomes on the random input parameters were readily obtained, e.g., PFS calculates automatically correlation coefficients and it can be used to present the results as histograms.

For each simulation, it was studied when the temperature of the insulating material around the metal wires reaches the critical temperature. The results included also smoke detector alarm time for each simulation. In the old fire simulations and in the analysis thereafter some sensitivities of chosen values and/or modelling choices were not examined. For example, these include: How much smoke/temperature/radiation is able to block fire brigade operations at the doors and at what level (meters above floor) this smoke/temperature/radiation criteria is observed.

Therefore, the properties of the Monte Carlo fire simulation data have been analysed in more detail. The study concentrates on the simulations without the sprinkler system, because in the simulations the sprinkler system was able to prevent the cable failure when it was working. This analysis was started by Tyrväinen et al. (2020) and it was noted and concluded that:

- The fires can be classified to be small or large fires. About 40 % of the fires released less than about 1 GJ of energy and a little more than 50 % release more than 10 GJ. These fires represent different type of fires. Small fires are local fires that do not spread, whereas the large fires represent cable fires that spread along the cable trays (horizontally and/or vertically).
- Almost all small fires (< 1 GJ) are initiated at the cable trays that are close to the ceiling, whereas larger fires (> 1 GJ) are initiated at lower cable trays
- The detection time of the small fires does not vary very much. The fires are initiated close to the ceiling. The detection time spread is much larger for the large fires and there is not so noticeable trend with respect to the z coordinate of the initial fire.
- Previous results can be used to simplify the event tree based modelling of the cable room fire scenario. The small fires can be treated with a separate, very simple, event tree branch, because small fires do not produce damage to cables on the other redundancy group. The larger fires (> 1 GJ) are treated with a more complicated event tree model. The event tree of the large fires can be simplified by separating the detection time from the simulated fires. The detection time can be used as a distribution and not a part of the results of a specific fire simulation.

In this report the analysis continues by studying the dependencies between the assumptions made for the fire brigade actions and the fire progression in the simulated fires, where the sprinkler system was failed. The main interest is on the fire-fighting conditions that were evaluated in the fire simulations.

In the previous fire PRA analysis of the cable room fire scenario, the variables of interest were visibility, temperature and radiation at the doors of the room. For each variable and door, it was determined when the conditions became intolerable. However, the criteria for the firefighting conditions were taken at one level only (e.g., 1.5 m for visibility). This was an arbitrary choice and the sensitivity of the results of this choice is examined in Figures 3−5. Shown are the times when there is too much smoke (low visibility) at different doors at four different heights (h = 0.5, 1.0, 1.5, and 2.0 m above floor). Only the large fires (burned fire load > 1 GJ) are considered, because smaller fires do not produce cable damage and they can be treated by a different event tree branch. It is seen that the height where the visibility is taken does not significantly affect the results. The results are also consistent. The conclusion is, that the old analysis was not sensitive with respect to the chosen details that were used to estimate the visibility at the different doors. This outcome may only be valid for the analysed fire scenario. For the large fires, the smoke layer starts to descend fast after a while and the visibility is lost quite rapidly at this point.

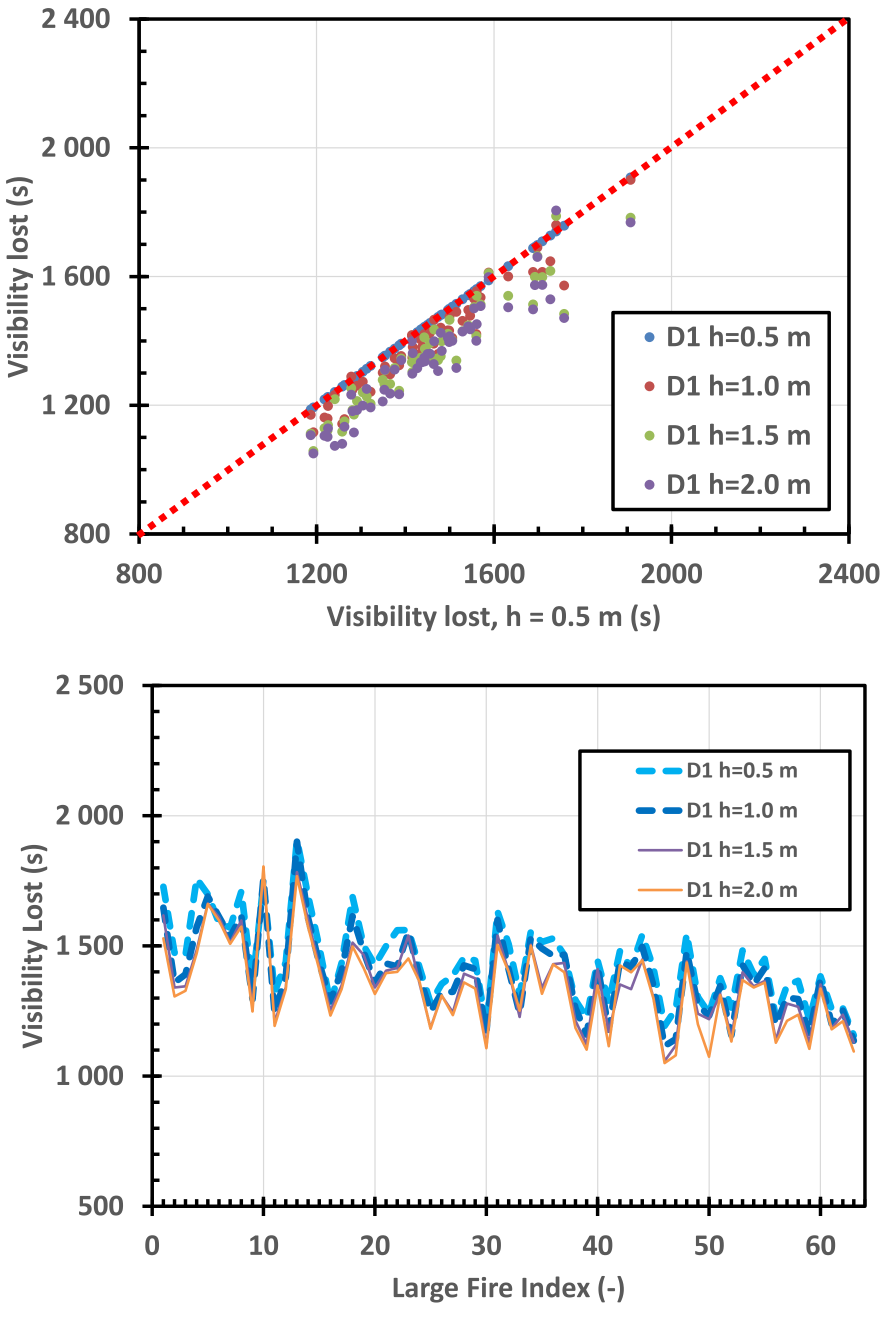

Figure 3: Fire brigade conditions at door 1 (D1): visibility criterion at four different heights (h = 0.5 m, 1.0 m, 1.5 m, 2.0 m). The height 0.5 m data is compared to other heights at the top and the times when visibility was lost in each simulation that produced "a large fire" are shown for each of the four heights at the bottom.

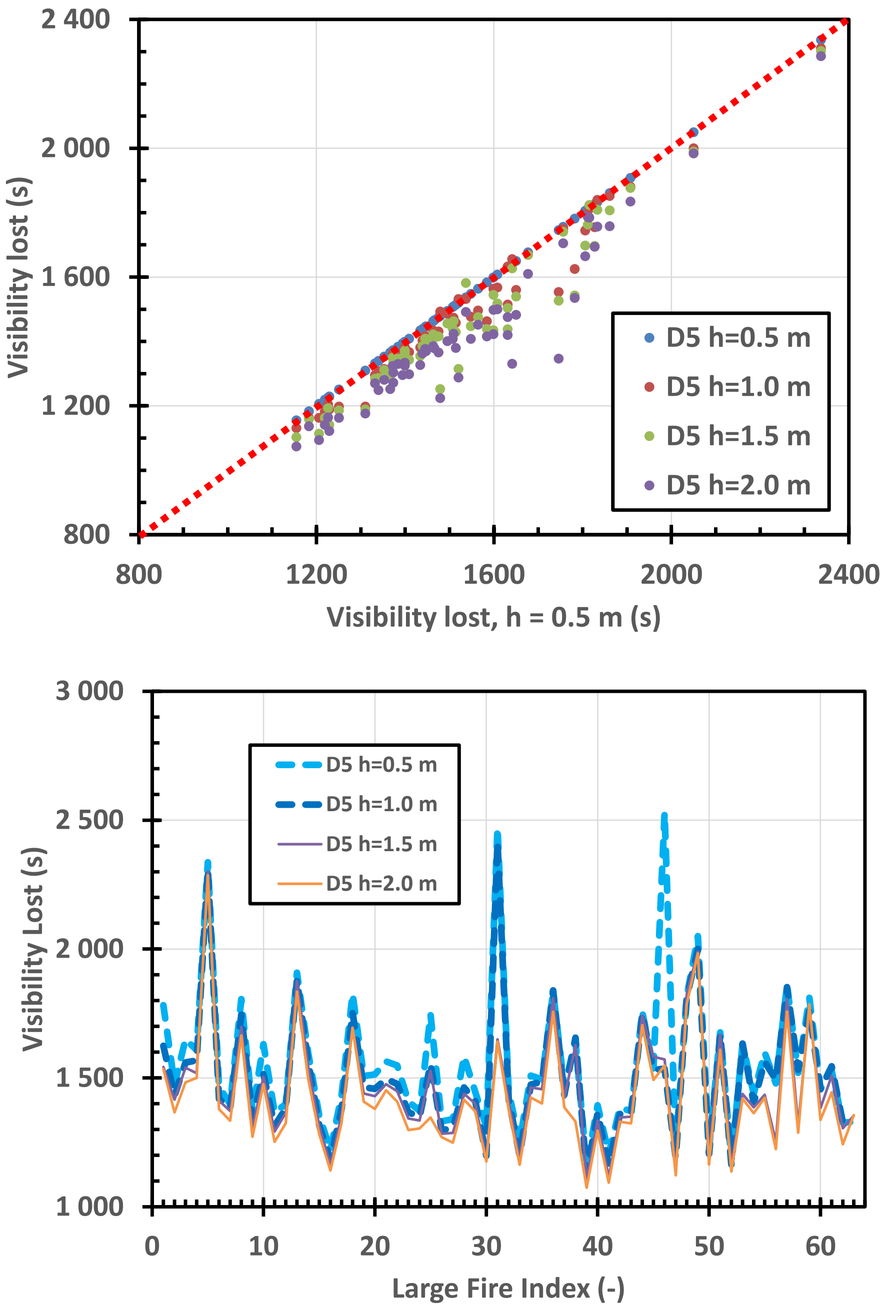

Figure 4: Fire brigade conditions at door 5 (D5): visibility criterion at four different heights (h = 0.5 m, 1.0 m, 1.5 m, 2.0 m). The height 0.5 m data is compared to other heights at the top and the times when visibility was lost in each simulation that produced “a large fire” are shown for each of the four heights at the bottom.

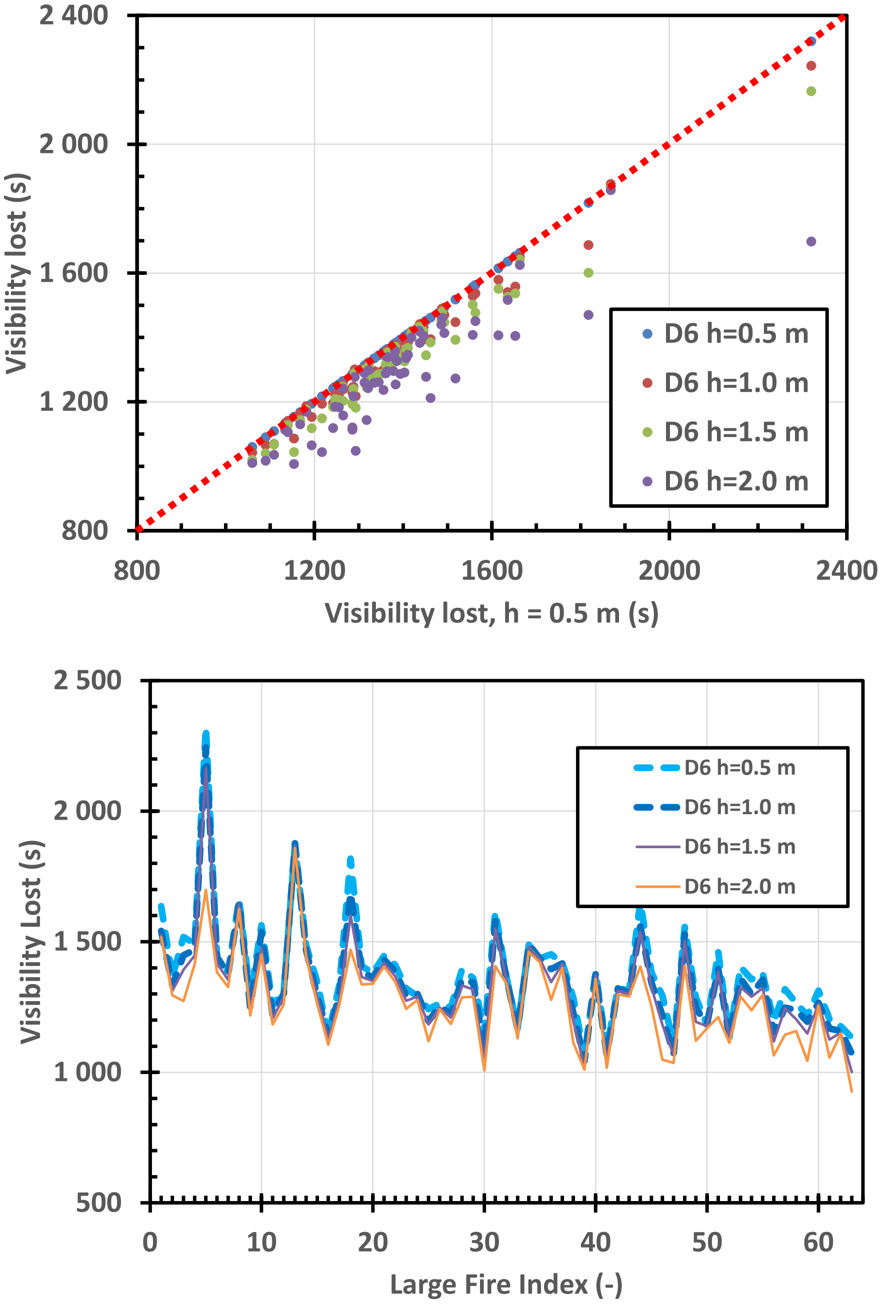

Figure 5: Fire brigade conditions at door 6 (D6): visibility criterion at four different heights (h = 0.5 m, 1.0 m, 1.5 m, 2.0 m). The height 0.5 m data is compared to other heights at the top and the times when visibility was lost in each simulation that produced "a large fire" are shown for each of the four heights at the bottom.

The effect of the arriving time of the fire brigade to the outcome of the analysis can be examined by comparing the cable damage time with the time at which the visibility is lost. If the cable damage occurs typically before the time when the visibility is lost, the visibility does not change the ability of fire brigade to prevent the cable damage. The damage is already happened, when the visibility is lost. Thus, the visibility does not have any effect on the outcome of the analysis in this case. On the other case, i.e., cable damage occurs typically after the loss of visibility, the fire brigade should come before the loss of visibility in order to have some effect on the outcome of the analysis (i.e., fire brigade might be able to prevent the cable damage).

Typically, in the cable room fire simulations the cable damage occurs very close to the time when the visibility criterion for successful fire brigade operations is lost on the doors, but for some fires the damage occurs much later than the visibility criteria for fire brigade operations is exceeded. In short, there are only a few cases where the smoke can have some effect to the outcome of the analysis. Most of the cases are such that if the smoke hinders fire brigade operations, the cable damage is already (or at about same time) happened and fire brigade could not suppress the fire in time even without the smoke. This conclusion is not sensitive to the actual cable damage criterion, both 180 °C and 215 °C cable failure temperatures show very similar behaviour. The same is true for the chosen level (height above the floor), where the smoke criterion for fire brigade operations is taken.

As can be seen in Figure 6, the cable failure time correlates strongly with the visibility criterion time of the fire brigade, especially for the door 1. For the other doors the correlation is not as strong, partly due to the fact that some of the other doors have only limited number of cases, where the smoke criterion is exceeded at all during the fire simulation. The general reason behind this correlation is physical. Fires that produce rapidly much smoke are typically also growing fast and, thus, able to damage cables fast. So there is a fundamental correlation between the smoke filling and cable damage times.

As stated above, the fire PRA model of the studied cable room fire scenario is not sensitive to the assumptions made for the operations of the fire brigade with respect to the conditions (smoke) in the room of fire origin. Partly this is due to the fact that typically the cable failure occurs at about the same time as conditions become unfeasible for the fire brigade to operate. Partly it is due to the fact, that the time that it takes for the fire brigade to be ready for its actions (be at the scene, voltage shut down, etc.), the cable failure has typically already occurred. This is partly due to the properties of the studied fire scenario, i.e. that the time when the visibility is lost at the doors is not sensitive to the details of how this visibility criteria is calculated. In Table 1 – Table 3 the distribution characteristics of the moments of loss of visibility are given for the doors 1, 5, and 6, respectively. It can be seen that the height above the floor, where the visibility information is taken, does not affect the distributions significantly.

Table 1: Parameters of the "visibility lost" time distribution at the door 1 for four different heights above the floor.

Door 1	**h=0.5 m**	**h=1.0 m**	**h=1.5 m**	**h=2.0 m**
ave	1440	1391	1356	1337
median	1438	1391	1345	1336
stddev	162	164	162	166
min	1156	1116	1058	1050
max	1908	1900	1788	1805

Table 2: Parameters of the "visibility lost" time distribution at the door 5 for four different heights above the floor.

Door 5	**h=0.5 m**	**h=1.0 m**	**h=1.5 m**	**h=2.0 m**
ave	1554	1501	1459	1421
median	1495	1463	1422	1377
stddev	281	249	223	223
min	1155	1131	1103	1074
max	2529	2416	2302	2286

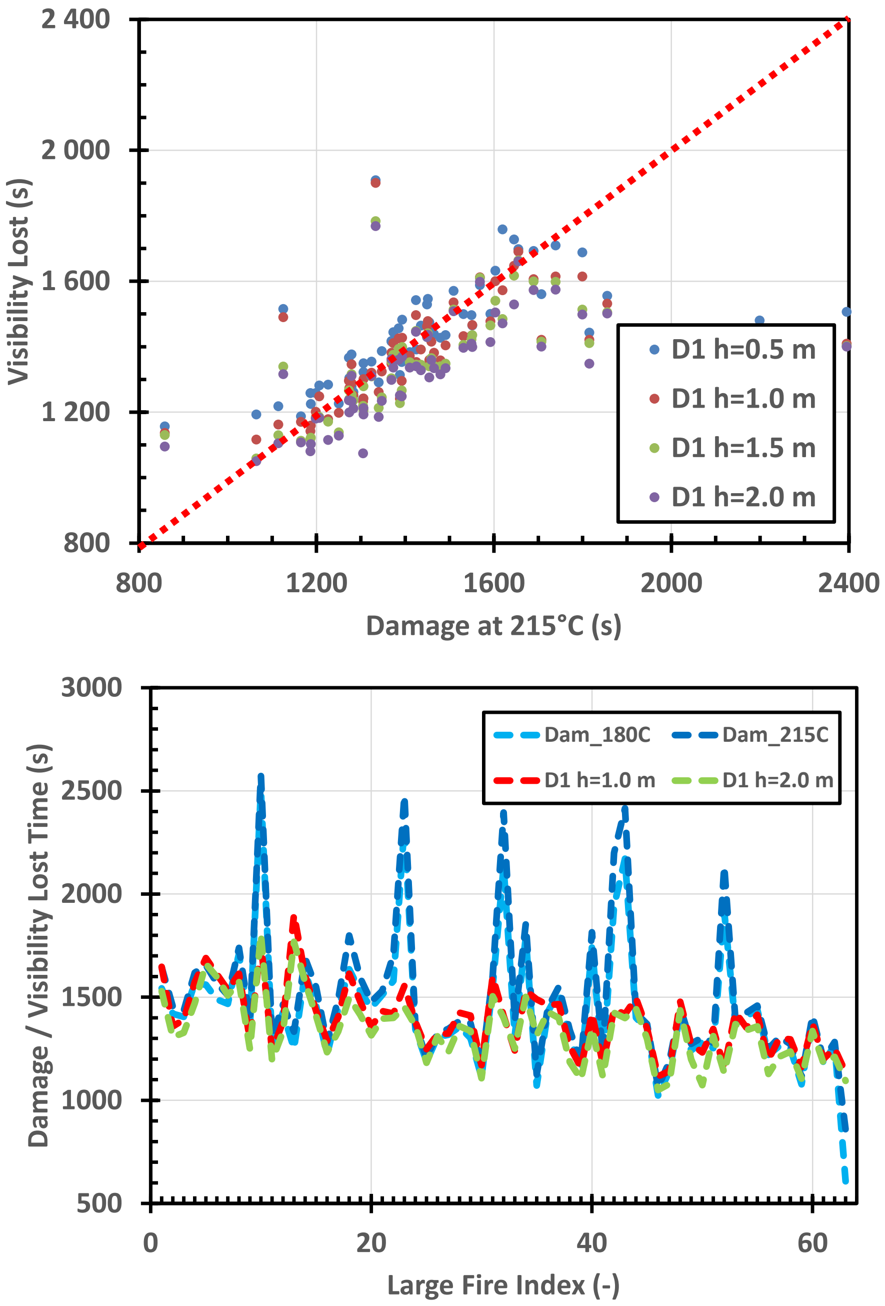

Figure 6: Fire brigade visibility criterion at door 1 vs. cable damage time. Top: visibility criterion at different heights (h = 0.5 m, 1.0 m, 1.5 m, 2.0 m) is compared to damage time. Bottom: The visibility criterion (h = 1.0 m, 2.0 m) and damage (180 °C and 215 °C damage temperatures) times in each simulation that produced "a large fire".

The ability of the fire brigade to operate in the room depends also on the room temperature. In the earlier analysis by Hostikka et al. (2012a) a temperature limit of 100 °C was used at the doors as the criterion to decide, if the fire brigade will try to enter the fire room. The times of exceeding 100 °C at the door 1 are compared to the cable failure times in Figure 7 and Figure 8. It can be seen that in this case the temperature is not a problem for fire brigade operations. For the other doors the temperature criterion is only exceeded in few simulations. It can be seen that the temperature criterion for fire brigade operations is sensitive to the height, where the temperature value is taken. But this sensitivity does not show in the results of the event tree analysis, because the visibility criterion is exceeded earlier than the temperature criterion, i.e., the smoke hinders the fire brigade operations first. It can also be seen, that the cable failure has already happened when the temperature criterion is exceeded, i.e., cables are damaged before it is too hot for fire brigade to operate.

Table 3: Parameters of the “visibility lost” time distribution at the door 6 for four different heights above the floor.

Door 6	**h=0.5 m**	**h=1.0 m**	**h=1.5 m**	**h=2.0 m**
ave	1374	1342	1320	1270
median	1356	1321	1312	1273
stddev	204	198	194	171
min	1060	1043	1001	926
max	2320	2244	2165	1858

As noted above, the temperature criterion for fire brigade operations is sensitive on how it is defined. Above a 100 °C temperature limit at different heights above the floor was examined. This is not an exact temperature limit, it is just an expert judgement. In actual situations the fire brigade does not measure the temperature exactly, but estimates the ability to enter the room otherwise. But if the temperature is about at this range, the thermal environment in the room is too hot for the fire brigade.

The effect of this somewhat arbitrary temperature threshold value choice is examined using three different values (80/100/120 °C) as the threshold temperature in Figure 9 and Figure 10, where the time distributions are shown for door 6 at two different heights above the floor (0.5 m and 1.5 m).

It can be seen that the time when the temperature criterion for fire brigade operations is exceeded is sensitive to how this criterion is defined. This is a natural feature that is due to the properties of the considered fire scenario. The space is quite air tight and the fire is mainly getting the needed fresh air from the ventilation system. Thus, the maximum heat release rates of the fires are not very high and the gas temperature in the room stays at moderate levels. Because these heavily under ventilated fires do not reach fully developed room fire conditions (flashover), also the fire brigade temperature criterion is sensitive to the level of the measuring point (height above the floor).

These sensitivities do not matter in this application of fire PRA method for the studied cable room fire scenario. The temperature criterion for fire brigade operations is exceeded in later stages of the fires when the cable failure has already happened and, thus, temperature has no impact on the fire brigade’s ability to suppress the fire before cable failure. Also the same reasons that were stated above for the smoke criterion apply here, e.g., typically fire brigade is ready for action too late to prevent the cable failure anyhow.

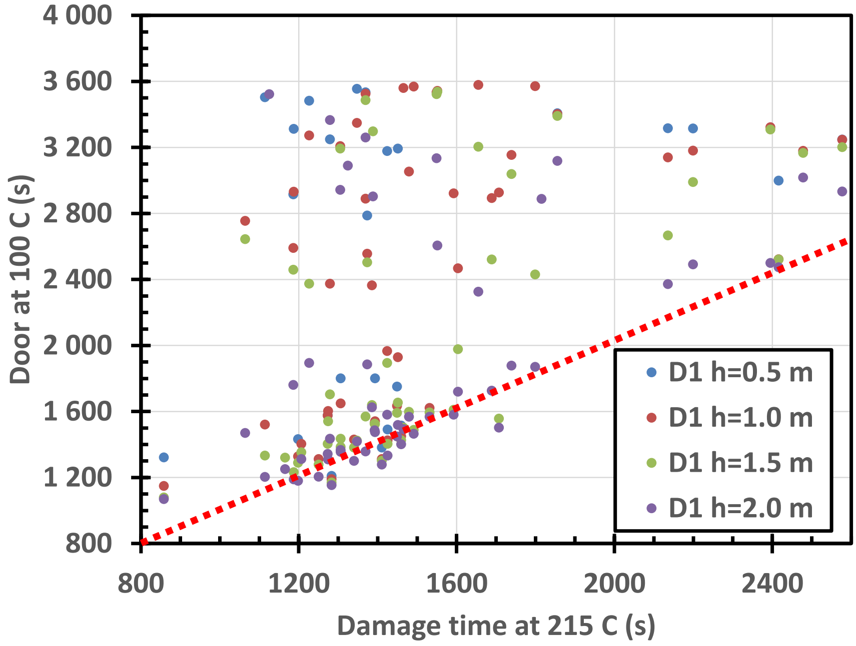

Figure 7: Damage time (cable failure at 215 °C) vs. “too hot for fire brigade” (100 °C) time at door 1 at four different heights above the floor.

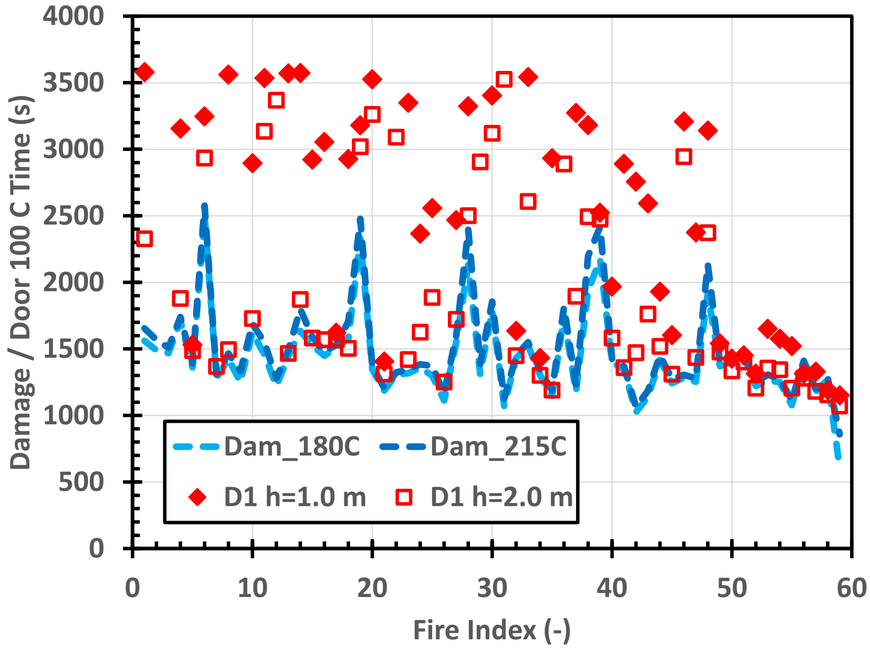

Figure 8: Damage times (both 180 °C and 215 °C failure temperatures) and “too hot for fire brigade” times (at two different heights above the floor) of the simulated large (> 1 GJ) fires at door 1.

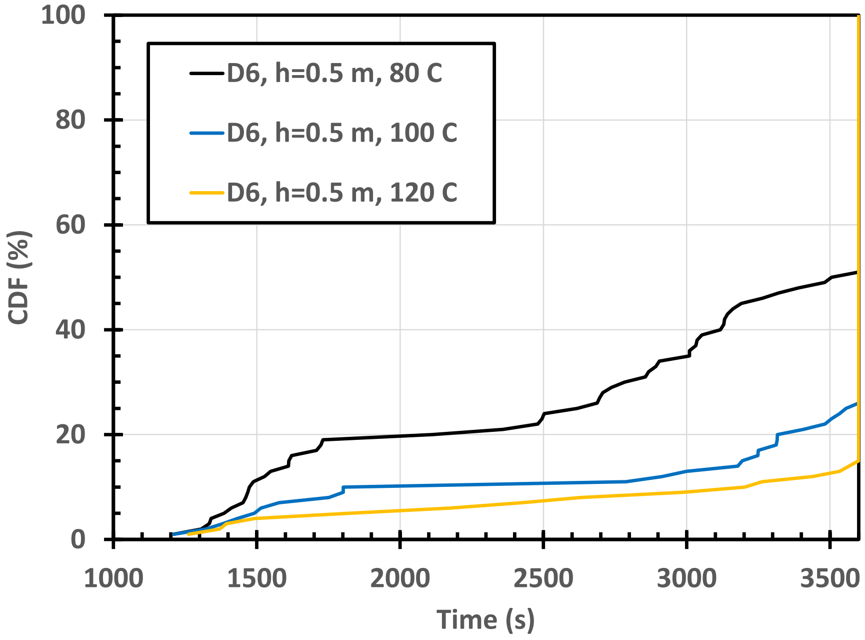

Figure 9: Cumulative distribution function of the “too hot for the fire brigade” time using three different temperature limits at 0.5 m above the floor at the door 6.

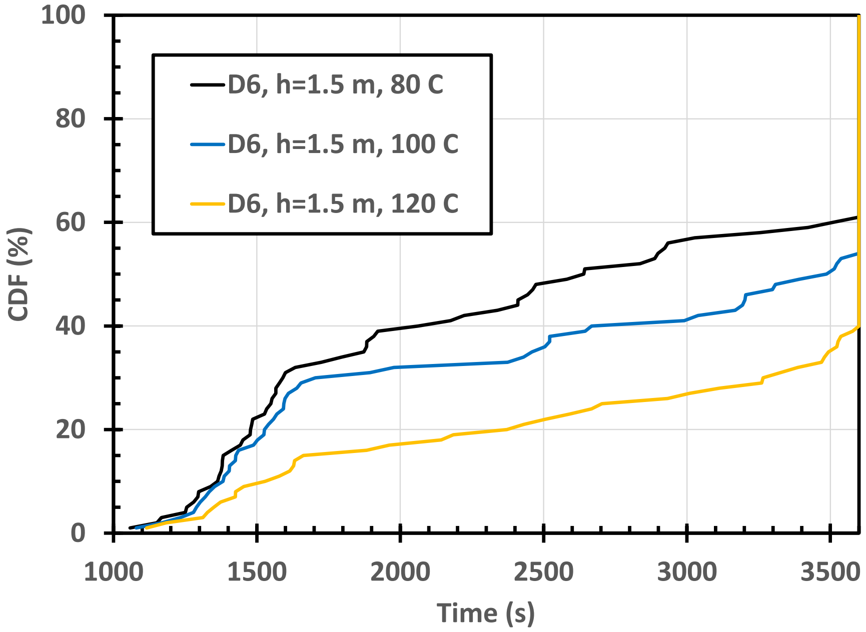

Figure 10: Cumulative distribution function of the “too hot for the fire brigade” time using three different temperature limits at 1.5 m above the floor at the door 6.

5. Uncertainties in the case study

The case study includes a large number of uncertainties. Some are obvious, whereas some are not so easily identified nor measured. Some uncertainties have already been taken into account in the model as probability distributions, whereas some have not. There are uncertainties related to fire simulation parameters, interpretation of fire simulation results, the fire simulation model itself, computation methods, time delays of firefighting actions, etc.

There are different types of uncertainties: parametric uncertainties, model uncertainties and completeness uncertainties. Uncertainties can also be categorised into epistemic and aleatory uncertainties (Jyrkama & Pandey 2016). Epistemic uncertainty is caused by lack of knowledge. Aleatory uncertainty is variability caused by inherent randomness of the system. For example, it is known that a toss of a coin can result in heads or tails with probability of 0.5, but it is uncertain which result is obtained by one toss. Aleatory uncertainty is naturally present in the system and cannot be reduced.

In the following subsections, uncertainties related to different areas of the analysis are identified. The significances of the uncertainties to the results are also analysed according to possibilities. Uncertainties are categorised into four significance categories: large, medium, small and insignificant. It has to be noticed that this categorisation is rough, and it is difficult to compare significances of uncertainties of difference types.

5.1 Fire simulation parameters

Uncertain parameters in fire simulations are presented in *Table 4*. Most of the parameters represent epistemic uncertainty. Some parameters are assumed to be associated with both epistemic and aleatory uncertainty, so they belong to a mixed category. In (Boneham et al. 2019), the maximum heat release rate has been classified as aleatory variable, but it is hard to believe that there would not be any epistemic uncertainty, i.e. that the triangular distribution would exactly represent the real variability of the parameter. Epistemic uncertainty should not be underestimated. Kloos et al. (2014) also list some fire simulation parameters with epistemic uncertainty that are partly same as here.

The parameters have also been qualitatively categorised according to their significance. The categorisation is based on how much the parameters impact the cable failure time according to Spearman's rank correlation coefficient (Dodge 2008). The time of maximum heat release rate is the parameter that has largest impact on the cable failure time. The activation temperatures of the sensors and response time indexes of the automatic suppression system are insignificant for the results, because the automatic suppression system was always able to suppress the fire when it worked.

The location of the initial fire was another parameter that was varied using uniform distributions. The location is associated with aleatory uncertainty, and the probability distribution of the location is associated with epistemic uncertainty. The location has medium significance to the results according to Spearman's rank correlation coefficient. The height of the initial fire has only small significance.

Table 4: Fire simulation parameters.

Parameter	Unit	Distribution	Significance	Uncertainty type
Maximum heat release rate of the initial fire	kW	Triangular(300,500,700)	Small	Mixed
Time of maximum heat release rate	s	Triangular(900,1200,1500)	Large	Mixed
Specific heat capacity of concrete	kJ/kg*K	Uniform(0.6,1)	Small	Epistemic
Density of concrete	kg/m^3	Uniform(2100,2500)	Medium	Epistemic
Thermal conductivity of concrete	W/m*K	Uniform(1.4,1.8)	Small	Epistemic
Thickness of cable sheath 1	mm	Uniform(2.184,3.276)	Medium	Epistemic
Thickness of cable sheath 2	mm	Uniform(2.184,3.276)	Medium	Epistemic
Thickness of cable insulation	mm	Uniform(2.56,3.84)	Medium	Epistemic
Thermal conductivity coefficient of cable sheath material		Triangular(0.7,1,1.3)	Small	Epistemic
Response time index 1	(m*s)^1/2	Triangular(120,150,180)	Insignificant	Epistemic
Response time index 2	(m*s)^1/2	Triangular(25,37.5,50)	Insignificant	Epistemic
Activation temperature 1	Celsius	Triangular(67,74,81)	Insignificant	Mixed
Activation temperature 2	Celsius	Triangular(50,57,64)	Insignificant	Mixed

5.2 Interpretation of the fire simulation results

The analysis includes parameters related to the interpretation of the fire simulation results, i.e. when the cable is considered to have failed and whether the fire brigade can enter the room. The parameters are presented in *Table 5*. Uncertainties related to these parameters have not been taken into account in the analysis, except that two separate values were used for cable failure temperature. Anyhow, some uncertainty is surely related to these parameters. There may be both epistemic and aleatory uncertainty. Cable failure temperature uncertainty is considered epistemic in (Boneham et al. 2019), but there could also be some variability, i.e. cable does not necessarily always fail in the same temperature. The critical height for safe and tolerable firefighting conditions depends on the firefighters, so that uncertainty could mostly be aleatory. However, the use of a constant height for the monitoring of the conditions in the simulation is a simplification and a source of uncertainty itself.

All the uncertainties related to the parameters have little, if any, significance to the results. In only 2% of the fire simulations, cable failure temperature 180 °C was reached, but not 215 °C, and usually 215 °C was reached soon after 180 °C. For firefighting conditions before cable failure, mainly the visibility limit, that is used to represent the critical firefighting conditions, has some significance. The height at which the visibility is measured also has only little significance as analysed in Section 4. The firefighter may enter the room crawling, but the visibility at 0.5 meters is usually lost quite soon (e.g. 1-2 minutes) after 1.5 meters as seen in Figure 3.

Kloos et al. (2014) had a different approach to the cable failure criteria: the cable was considered failed if it was exposed to a specific temperature a specific time. For example, 40 seconds in 180 °C would cause the failure, as well as 120 seconds in 170 °C. Probability distributions were also specified for the critical exposure times, and uncertainty analysis was performed. These type of criteria were preferred by Kloos et al. (2014) over simple temperature criterion, and it had a large impact on the results. Therefore, the uncertainty related to the cable failure criteria should not be underestimated.

Table 5: Parameters used in interpretation of the fire simulation results.

Parameter	**Unit**	**Value**	**Significance**	**Uncertainty type**
Cable failure temperature	°C	Two options: 180, 215	Small	Mixed
Visibility limit for fire fighting	m	1	Small	Mixed
Temperature limit for fire fighting	°C	100	Small	Mixed
Radioactive heat flux limit for fire fighting	kW/m^2	10	Insignificant	Mixed
Critical height for firefighting conditions	m	1.5	Small	Mixed

5.3 Operation time model for firefighting

The parameters of the operation time model are presented in Tables 6−13. There are two types of variables: time delays and probabilities. Uncertainties related to probabilities are epistemic. Time delays have typically both aleatory and epistemic uncertainty, because a specific action lasts different time on different trials, but the real probability distribution of the time delay is not known exactly. Aleatory and epistemic uncertainties have not been separated in the model.

A couple of parameters do not have uncertainty distributions assigned to them, but it seems likely that there is anyway some uncertainty. Particularly, the time to the room entrance should have some aleatory uncertainty, because it is hard to believe that the walk would always take the same time. Furthermore, there should also be some epistemic uncertainty. The probabilities of road barrier and other alarm could also have some epistemic uncertainty, even if there is lots of data available about those.

Table 6: Parameters of the detection model.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Automatic detection failure probability		Uniform(0.001,0.02)	Small	Epistemic
Probability of detection from another room		Uniform(0.001,0.002)	Small	Epistemic
Time of detection from another room	min	Uniform(1,15)	Small	Mixed
Time of manual detection	min	Uniform(1,120)	Small	Mixed
Time of automatic detection	min	Lognormal(1.23,2.46)	Small	Mixed

Table 7: Guard centre model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Auto-notification failure probability		Uniform(0.01,0.05)	Small	Epistemic
Probability of wrong address		Uniform(0.01,0.05)	Small	Epistemic
Probability of wrong interpretation of the alarm		Uniform(0.01,0.05)	Small	Epistemic
Time delay of making a collective alarm	min	Uniform(0.1,0.5)	Small	Mixed
Time delay of calling the unit director	min	Uniform(1,1.5)	Small	Mixed
Time delay caused by wrong address	min	Uniform(2,10)	Small	Mixed
Time delay of alarm set-off	min	Uniform(0.5,5)	Medium	Mixed
Time delay caused by wrong interpretation of the alarm	min	Uniform(1,10)	Small	Mixed
Time delay of calling to the guard centre	min	Uniform(0.5,2)	Small	Mixed

Table 8: Control room model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Probability of credibility gap		Uniform(0.01,0.1)	Small	Epistemic
Probability that voltage is not switched off		Uniform(0.03,0.3)	Small	Epistemic
Time delay of sending a person to ensure fire	min	Uniform(0.5,2)	Small	Mixed
Time delay of collaboration	min	Uniform(1,10)	Medium	Mixed
Time delay caused by credibility gap	min	Uniform(3,5)	Small	Mixed
Time delay of switching off the voltage	min	Uniform(10,30)	Small	Mixed
Time delay caused by failure to switch off the voltage	min	Uniform(10,30)	Small	Mixed

Table 9: Fire confirmation model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Probability of choosing a wrong route		Uniform(0.01,0.1)	Small	Epistemic
Time delay of moving to the starting point	min	Uniform(0,15)	Medium	Mixed
Time delay of walking to the room of origin	min	Uniform(2,3)	Small	Mixed
Time delay of choosing a wrong route	min	Uniform(1,15)	Small	Mixed

Table 10: Fire brigade response time model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Fire brigade response time	min	Gamma(2.82,0.27)	Small	Mixed
Probability of wrong target		Uniform(0.02,0.2)	Small	Epistemic
Unavailability of crew		Uniform(0.05,0.5)	Small	Epistemic
Unavailability of equipment		Uniform(0.01,0.1)	Small	Epistemic
Probability of route barrier		0.06		
Probability of other alarm		0.03		
Time delay caused by wrong target	min	Uniform(2,4)	Small	Mixed
Time delay caused by unavailable crew	min	Uniform(5,8)	Small	Mixed
Time delay caused by unavailable equipment	min	Uniform(5,10)	Small	Mixed
Time delay caused by route barrier	min	Uniform(5,10)	Small	Mixed
Time delay caused by other alarm	min	Uniform(10,15)	Small	Mixed

Table 11: Building entrance model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Probability of broken hose		Uniform(0.02,0.1)	Small	Epistemic
Probability of broken coupling		Uniform(0.01,0.05)	Small	Epistemic
Pump failure to start probability		Uniform(0.01,0.05)	Small	Epistemic
Time to the building entrance	min	Uniform(0.5,5)	Small	Mixed
Time delay caused by broken hose	min	Uniform(2,4)	Small	Mixed
Time delay caused by broken coupling	min	Uniform(2,4)	Small	Mixed
Time delay caused by pump failure to start	min	Uniform(2,4)	Small	Mixed

The significance of different uncertainties was analysed by sensitivity analysis, where the analysed parameter was set to the “best possible value”. If the cable failure probability decreased less than 1E-3, the uncertainty was assessed to have small significance. It can be seen from the results that individual parameters do not have much significance. Only four time delay parameters with large uncertainty are assessed to have medium significance. These time delays are such that they occur with certainty and are not related to human failures or component failures.

Table 12: Fire brigade to the room model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Probability that keys are forgotten		Uniform(0.02,0.2)	Small	Epistemic
Probability that wedges are forgotten		Uniform(0.02,0.2)	Small	Epistemic
Probability of broken hose		Uniform(0.05,0.3)	Small	Epistemic
Time to the room entrance	min	0.462	Small	Mixed
Time delay caused by forgotten keys	min	Uniform(3,6)	Small	Mixed
Time delay caused by forgotten wedges	min	Uniform(1,2)	Small	Mixed
Time delay caused by broken hose	min	Uniform(1,2)	Small	Mixed

Table 13: Systematic search model parameters.

Parameter	**Unit**	**Distribution**	**Significance**	**Uncertainty type**
Probability that the thermal camera is forgotten		Uniform(0.02,0.2)	Small	Epistemic
Probability of pressure loss		Uniform(0.05,0.3)	Small	Epistemic
Probability of communication problem		Uniform(0.05,0.3)	Small	Epistemic
Time delay of systematic search	min	Uniform(0,7)	Medium	Mixed
Time delay caused by forgotten camera	min	Uniform(0,3)	Small	Mixed
Time delay caused by pressure loss	min	Uniform(1,5)	Small	Mixed
Time delay caused by communication problem	min	Uniform(2,5)	Small	Mixed

5.4 Other uncertainties

The failure probability of the automatic suppression system is a very important parameter for the results and quite uncertain. A uniform distribution between 0.02 and 0.04 has been used for it so far, but it hardly represents the complete uncertainty of the probability and should be revised. Therefore, the reliability analysis of sprinkler systems will be studied in Section 6.

Uncertainties related to the models and the completeness of the analysis are more difficult to assess. There is epistemic uncertainty with regard to the accuracy and correctness of the FDS model including the ventilation model, smoke detectors model, sprinklers model, material parameters, ignition and combustion model. Analysis of model uncertainty in the context of fire simulations has been studied in (Paudel & Hostikka 2019). There can also be uncertainty with regard to the FinPSA model and particularly the operation time model, e.g. concerning the completeness and correctness, but likely parameter uncertainties are more significant.

There is finally uncertainty concerning how realistically FDS calculates the fire progression based on given input parameters. The coverage of the simulations is also one source of uncertainty. In FinPSA, the uncertainty related to 10000 simulation cycles is only small, because the result does not vary much between different trials. In fire simulations, only 100 cycles were performed, but on the other hand, efficient Latin hypercube sampling was used. It is not known how much the accuracy would be improved, if the number of fire simulations was increased.

5.5 Uncertainty analysis

Comprehensive uncertainty analysis would require that quantitative distributions could be assigned to all significant uncertainties. Aleatory and epistemic uncertainties should also be represented by separate distributions, e.g. so that epistemic uncertainty distributions would be assigned to the parameters of aleatory uncertainty distributions. The reason for this is that the probability of the cable failure itself represents the aleatory uncertainty on the occurrence of the cable failure, and the uncertainty distribution of the probability should represent uncertainty due to lack of knowledge, i.e. epistemic uncertainty. For each variable, it should be analysed what is the uncertainty caused by lack of knowledge (epistemic) and what is the uncertainty caused by the randomness of the action or event (aleatory). The uncertainty analysis could e.g. be performed by sampling epistemic and aleatory variables in separate loops as presented in (Tyrväinen & Karanta 2019) and (Boneham et al. 2019). However, this type of functionality has not yet been implemented in FinPSA.

6. Reliability of a sprinkler system

It has not been a standard practise in fire PRA applications to conduct reliability analyses for sprinkler systems. Therefore, there are not much failure data available for sprinkler components. In fire PRA, very conservative failure probabilities are typically used for sprinkler systems. EPRI’s fire PRA guide (EPRI & U.S. NRC 2005) considers generic system level failure probabilities from 0.02 to 0.05 depending on the type of the system to be realistic.

6.1 Literature

According to Nieminen (2018) there are two different methods to assess the reliability of sprinkler systems: a system based method and a component based method. In the system based method, previous fire cases are studied from compiled databases and statistics for direct evaluation of the reliability of the entire sprinkler system. In the component based method a fault tree is formed for the hardware components, reliability estimates are determined for individual hardware components, and the probability of failure is calculated for the top event.

Accident-based studies of non-nuclear applications have shown that the majority of failures are due to inadequate maintenance or human error (the system is turned off) and failures due to actually failed components are very rare (Hall 2013; Hall 2010; Nieminen 2018). Statistics based reliability assessments always consist of a number of different sprinkler systems, so the component-based method is better suited for a single site to assess the reliability of a specific sprinkler system.

There have been some attempts on fault tree modelling of sprinkler systems (Nieminen 2018; Rönty et al. 2004), but the uncertainties seem to be very large in such analyses. Nieminen

(2018) estimated a failure probability of 0.003-0.01 for a generic non-nuclear sprinkler system in his recent master's thesis. The model includes failures of the general water pipe, check valve, wet alarm valve, electric pump, diesel pump, piping and sprinkler head. The failure probabilities of the components were collected from literature, and the whole range of available values was used in the uncertainty analysis. Mission time of three months was used for most components, because the system should be tested every three months. This is a conservative approach, since the system obviously does not need to work the whole testing interval. Possibility that too many sprinkler heads open causing ineffective fire suppression was also modelled. If there are too many opening sprinkler heads relative to the amount of water available, then the amount of water coming from a single sprinkler may not be sufficient to ensure effective fire control.

Rönty et al. (2004) studied sprinkler system reliability with focus on nuclear power plant systems. Failure data from Finnish nuclear power plants was collected in that study, and failure rates/probabilities were estimated for different components. The data may be outdated now as at least Olkiluoto's systems have been renewed, but there are no newer studies on nuclear power plants available. There are some sprinkler system data available from other domains, such as (Frank et al. 2013; Moinuddin & Thomas 2014), but mostly the data are very old and their applicability is difficult to judge.

6.2 Fault tree example

Here, we present a simplified fault tree analysis of a generic wet pipe sprinkler system. Components of the system include a check valve, a wet alarm valve, sprinkler heads and three pumps. One of the pumps is a motor-operated pump, and two of the pumps are diesel pumps. One of the pumps is required to start and supply water to the sprinklers if a fire occurs.

It is assumed that only one sprinkler head is important for fire suppression. If it fails, the fire suppression fails. This is presumably a conservative assumption, because other sprinkler heads could possibly make up the failure of the nearest sprinkler head.

The position of the check valve is assumed to be monitored, but the possibility that the monitoring fails is also modelled.

Other components like pipes, water source and valves on water supply lines from the pumps to the sprinklers are left out of this analysis. It is assumed that severe failures of those components would likely be noticed soon, and the probabilities to fail during the fire event are small.

The top fault tree for the sprinkler system is presented in *Figure 11*, and the fault trees of the pumps are presented in Figures 12−14. Pump 1 is the motor-operated pump. For the pumps, unavailability due to maintenance have been modelled in addition to pump failures. For the motor-operated pump, power supply failures have simply been modelled using a single basic event, even though the power supply system would require its own fault tree in reality.

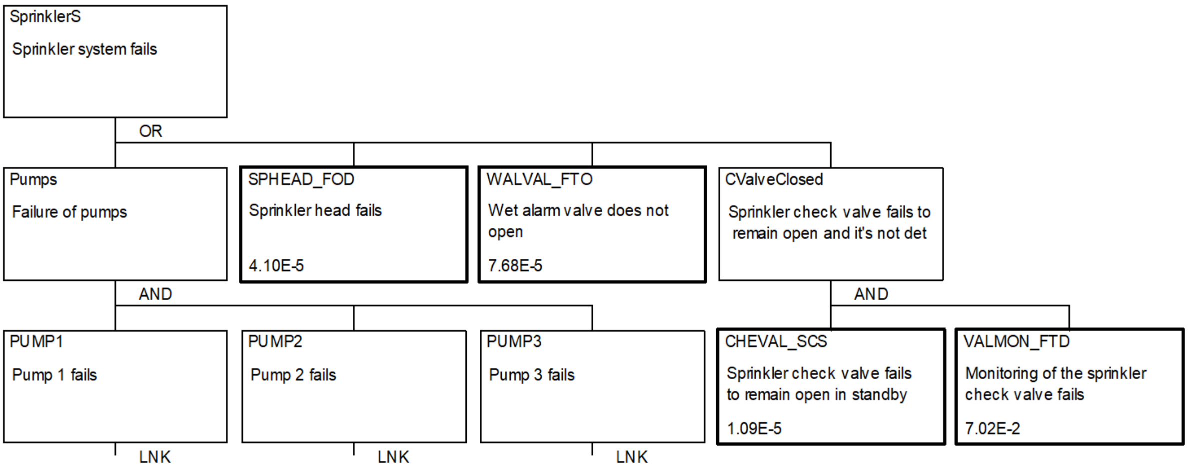

Figure 11: Fault tree for the sprinkler system.

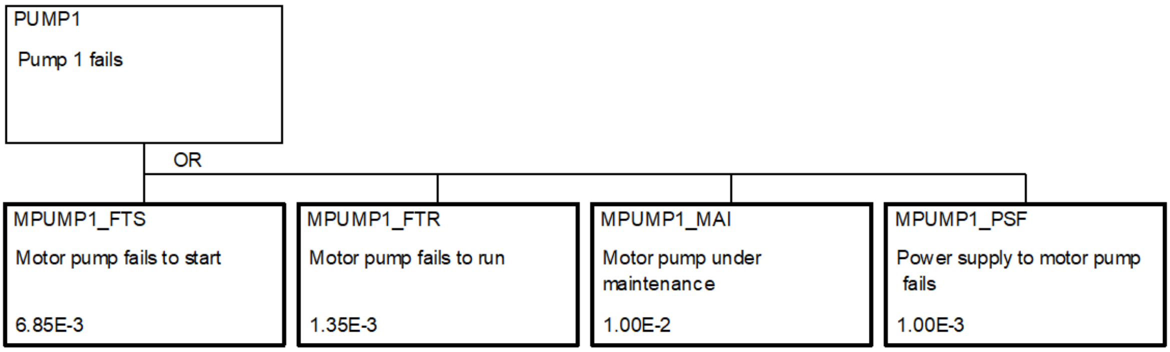

Figure 12: Fault tree for pump 1.

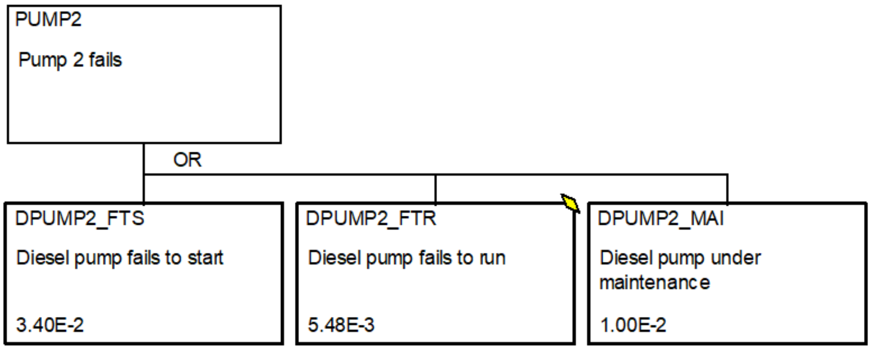

Figure 13: Fault tree for pump 2.

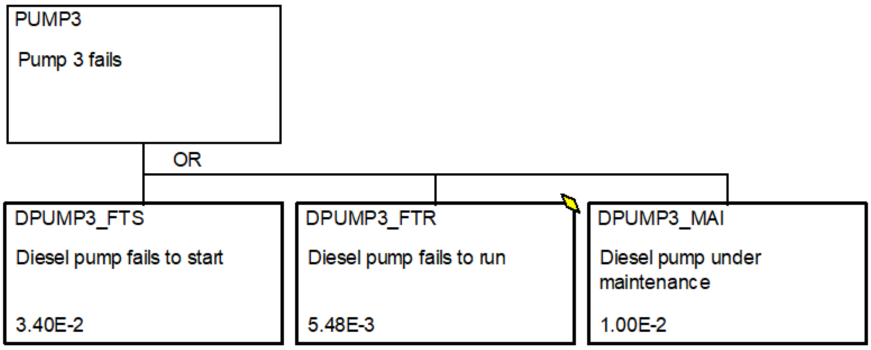

Figure 14: Fault tree for pump 3.

The failure rates and probabilities used in the analysis are presented in *Table 14*. They have been taken from several different sources. Typically, conservative 95th percentile values have been selected. The failure rates of the pumps are generic values from T-Book (TUD Office 2015). The probabilities of maintenance and power supply failure basic events are made up, but the order of magnitude is realistic.

Table 14: Failure rates and probabilities of the basic events.

Name	Comment	Fr	Probability	Source
CHEVAL_SCS	Sprinkler check valve fails to remain open in standby	1.01E-8	1.09E-5	NRC 2016b
DPUMP2_FTR	Diesel pump fails to run	5.50E-3	5.48E-3	T-Book
DPUMP2_FTS	Diesel pump fails to start	9.80E-5	3.40E-2	T-Book
DPUMP2_MAI	Diesel pump under maintenance	0	1.00E-2	
DPUMP3_FTR	Diesel pump fails to run	5.50E-3	5.48E-3	T-Book
DPUMP3_FTS	Diesel pump fails to start	9.80E-5	3.40E-2	T-Book
DPUMP3_MAI	Diesel pump under maintenance	0	1.00E-2	
MPUMP1_FTR	Motor pump fails to run	1.35E-3	1.35E-3	T-Book
MPUMP1_FTS	Motor pump fails to start	2.03E-5	6.85E-3	T-Book
MPUMP1_MAI	Motor pump under maintenance	0	1.00E-2	
MPUMP1_PSF	Power supply to motor pump fails	0	1.00E-3	
SPHEAD_FOD	Sprinkler head fails	1.22E-7	4.10E-5	Rönty 2004
VALMON_FTD	Monitoring of the sprinkler check valve fails	0	7.02E-2	Moinuddin 2014
WALVAL_FTO	Wet alarm valve does not open	2.28E-7	7.68E-5	Rönty 2004

For the wet alarm valve, the failure rate is taken from Finnish non-nuclear statistics (Rönty et al. 2004), even though there is some nuclear-specific data available in the same reference. The choice was made, because the data from nuclear domain is scarce, and non-critical failures are included in the data. With this value, the results are more balanced, but it has to be noticed that e.g. for Loviisa turbine hall ceiling protection system, a much larger failure rate has been estimated (Rönty et al. 2004).

For the sprinkler head, the failure rate was taken from old Olkiluoto data counting both critical and “consequentially critical” failures (Rönty et al. 2004). The failure rate of the check valve was taken from NRC’s database. Much larger values can also be found from sprinkler related literature, but larger values seem somewhat questionable, since e.g. in (Nieminen 2018), it is stated that check valves do not close spuriously, and the only possibility for failure is a maintenance failure.

A testing interval of a month is applied to most of the components. For the check valve, the testing interval is three months. Mission time of an hour is used for the pumps. It is a conservative value as the fire typically lasts a shorter time when the sprinkler system works.

A common cause failure (CCF) for failure to run events of the diesel pumps is modelled with conservative 95th percentile beta-factor value from (NRC 2016a). The value is based on motor-operated pumps, because data for diesel pumps were not available. A CCF is not modelled for failure to start events, because the probability of a single failure is itself larger than the beta-factor would be.

The top event probability is 1.64E-4. The most important minimal cut sets are the following:

Num	Freq.	Cumul	Name	Comment
1	7.66E-05	46.66	WALVAL_FTO	Wet alarm valve does not open
2	4.10E-05	71.62	SPHEAD_FOD	Sprinkler head fails
3	1.15E-05	78.66	DPUMP2_FTS	Diesel pump fails to start
			DPUMP3_FTS	Diesel pump fails to start
			MPUMP1_MAI	Motor pump under maintenance
4	7.91E-06	83.47	DPUMP2_FTS	Diesel pump fails to start
			DPUMP3_FTS	Diesel pump fails to start
			MPUMP1_FTS	Motor pump fails to start
5	4.60E-06	86.28	DPUMPX_FTR-AB	2x CCF Diesel pumps fail to run
			MPUMP1_MAI	Motor pump under maintenance
6	3.15E-06	88.20	DPUMPX_FTR-AB	2x CCF Diesel pumps fail to run
			MPUMP1_FTS	Motor pump fails to start
7	2.33E-06	89.61	DPUMP2_MAI	Diesel pump under maintenance
			DPUMP3_FTS	Diesel pump fails to start
			MPUMP1_FTS	Motor pump fails to start
8	2.33E-06	91.03	DPUMP2_FTS	Diesel pump fails to start
			DPUMP3_MAI	Diesel pump under maintenance
			MPUMP1_FTS	Motor pump fails to start
9	1.86E-06	92.17	DPUMP2_FTS	Diesel pump fails to start
			DPUMP3_FTR	Diesel pump fails to run
			MPUMP1_MAI	Motor pump under maintenance
10	1.86E-06	93.30	DPUMP2_FTR	Diesel pump fails to run
			DPUMP3_FTS	Diesel pump fails to start
			MPUMP1_MAI	Motor pump under maintenance

The failure of the wet alarm valve is the most important event of the model, but also pump failures and sprinkler head failure contribute significantly to the total result. The check valve is not important, because of the smaller failure probability and monitoring.

The total probability is very small compared to the values used in the fire PRA model and some values in the literature, but uncertainties are large. It can mainly be concluded that the risk related to pump failures is small, if there are three pumps and one of the pumps is of different type. For the pumps, there are sufficient data available, and conservative 95th percentile values were used. On the other hand, the failure probabilities of the sprinkler head and wet alarm valve are quite uncertain, as also larger values can be found from literature. If the value estimated for a wet alarm valve in Loviisa turbine hall ceiling protection system in (Rönty et al. 2004) was used, the failure probability of the wet alarm valve would be 3.5E-3 and it would completely dominate the result.

Collection of sufficient amount of failure data for sprinkler system components is necessary for credible reliability analysis. It is important to separate different failure modes and impacts. Particularly critical failures need to be separated from failures that do not prevent the fire suppression as recognized by Rönty et al. (2004).

The completeness of the analysis is important to evaluate. Some sprinkler system failure studies indicate that minority of failures to suppress are caused by component failures (Nieminen 2008). Common reasons for failures include that system was shutdown, design fault, lack of maintenance and manual intervention. It can be expected that in a nuclear power plant environment such faults would be less likely, but still those should not be ruled out without sufficient consideration. Probabilities of such failures are, of course, difficult to estimate, unless some general sprinkler system statistics are used.

7. New modelling issues

The purpose of this section is to consider fire PRA modelling issues that do not appear in the original cable fire case study. Some modelling issues are identified from literature and some based on general knowledge on fire modelling problems. It is considered how different modelling issues could be incorporated into the analysis.

7.1 Multiple cable failures

It is fairly common to study multiple consequences in fire PRA, e.g. failures of different cables in the same room. For example, Boneham et al. (2019) present a study with multiple cable trays, which is quite comparable to our case study. Different cable failures can simply be modelled as different end states of the event tree. Cases with only one cable failure, failure of all cables in the room and combinations of cable failures can be modelled as separate event tree sequences.

Fire simulations need to produce failure times for all target cables, and those can be imported to FinPSA as vectors in the same way as in the case of one target. The event tree can be constructed e.g. as in *Figure 15* so that different consequences have separate branches in the last section of the event tree. When calculating the failure probabilities, one has to remember that the cable failure times of different cables are dependent, i.e. they cannot be treated independently. Because of this, it is convenient to handle different cables in the same event tree section. The programming can then be performed as in the following scripts (find the original scripts in (Tyrväinen et al. 2020)).

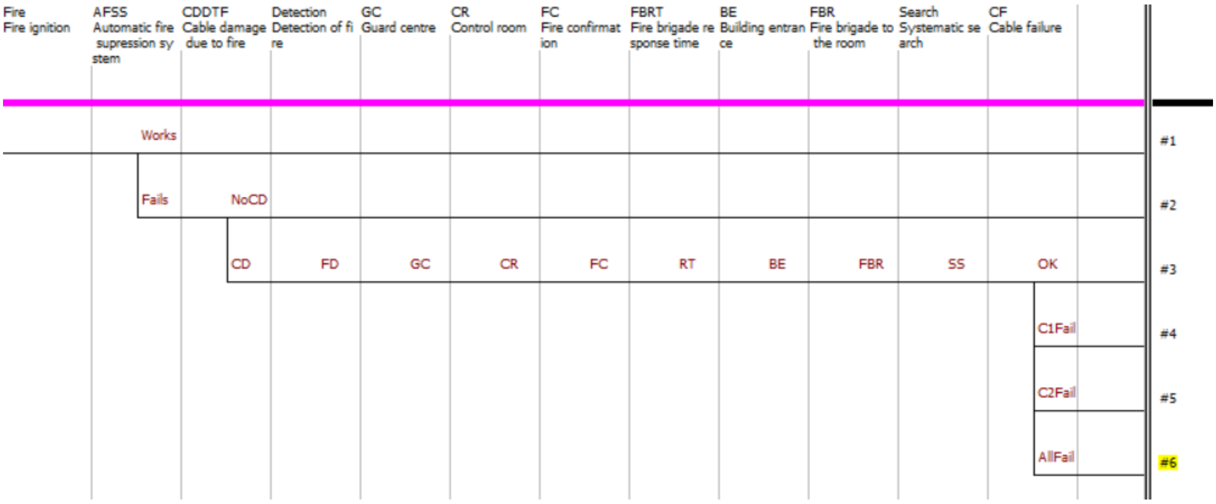

Figure 15: Event tree with two target cables.

```
function real AllFail
  i = 1
  c = 0

  while lesse(i,NumSim) do
  begin
    if lesse(BadConditions(i),t_oper-t_ss) then
    begin
      $ Not possible to enter the room due to intolerable conditions
      c = c+1
    end
    else if lesse(DamageTime1(i),t_oper) then
    begin
      if lesse(DamageTime2(i),t_oper) then c = c+1
    end
    i = i+1
  end

  $ Probability of cable failure
  p_all = c/NumSim

  Damage1 = true
  Damage2 = true
return p_all


function real C1Fail
  i = 1
  c = 0

  while lesse(i,NumSim) do
  begin
    if more(BadConditions(i),t_oper-t_ss) then
    begin
      if lesse(DamageTime1(i),t_oper) then
      begin
        if more(DamageTime2(i),t_oper) then c = c+1
      end
    end
    i = i+1
  end

  $ Probability of cable failure
  p_1 = c/NumSim

  Damage1 = true
  Damage2 = false
return p_1


function real C2Fail
  i = 1
  c = 0
```

```
  while lesse(i,NumSim) do
  begin
    if more(BadConditions(i),t_oper-t_ss) then
    begin
      if lesse(DamageTime2(i),t_oper) then
      begin
        if more(DamageTime1(i),t_oper) then c = c+1
      end
    end
    i = i+1
  end

  $ Probability of cable failure
  p_2 = c/NumSim

  Damage1 = false
  Damage2 = true
return p_2
```

If the order of cable failures is important for functioning/failure of the corresponding safety functions, that is also simple to take into account with a couple of changes to the scripts.

7.2 Fire spreading outside the room

Fire spreading outside the room is one consequence of interest related to the cable room fire case study. The performance of the fire compartmentation of the cable room was studied in (Paajanen & Kling 2013) by continuing the simulations of (Hostikka et al. 2012a) for an extended period of time to determine the four-hour exposure. From the simulations, it was concluded that in this kind of environment, it would take several hours for the thermal exposure to reach the followed fire barriers. Beyond this, there is a risk of fire spreading if a door of the room is open or not intact. Through an open door, the fire also receives oxygen, which could also affect the fire and make it much worse.

In the FinPSA model, the event tree could have separate branches for the cases where the door is open. It could be asked in the beginning of the event tree or after the automatic suppression system failure, depending on whether it affects the success of the suppression system. Separate fire simulations would then be required for the open door case, and the probability of open door should be estimated.

Modelling of fire spreading would require some more information from fire simulations. For each fire simulation, it should be determined whether the fire spreads outside the room or a probability for that should be estimated. This could e.g. mean comparison of the thermal exposure of a fire barrier to the strength of the fire barrier. The analysis could be done either in background calculations or inside the FinPSA model if sufficient information about fire and structures were imported to the model. Also, if background calculations were used, the results of those should be imported to the FinPSA model. Fire spreading could be modelled with an additional event tree section after the cable failure consideration. The dependency between the cable failure and fire spreading should however be taken into account in the calculations, because the model would include such consequences as “cable failure with fire spreading”, “cable failure without fire spreading” and “fire spreading without cable failure”.

7.3 Multiple fire brigades

Kloos et al. (2014) have modelled a pump lubrication oil fire in NPP using a dynamic event tree. Cable failure is also analysed in this study, and the study is comparable to our study. A particularly interesting aspect of that study is that the fire can be suppressed by a fire patrol or a fire brigade. If two out of three detectors detect the fire, both the fire patrol and fire brigade are alarmed immediately. If only one detector detects the fire, the fire patrol inspects the compartment. The fire patrol always arrives first to the compartment, but the fire patrol does not wear personal protective equipment and is not able to extinguish all fires.

To model similar case with our method, the operation times of both the fire patrol and fire brigade would need to be considered. This would be easy to model given sufficient information about the time delays. The fire patrol is likely to correspond to the person who confirms the fire in the cable room fire case. Therefore, the fire extinguishing would be the only new part in the model. It would then need to be considered what the conditions for successful firefighting of the fire patrol are, and how long time the extinguishing would take. The modelling of the success/failure could be performed simply by adding a couple of new if-clauses to the scripts. It might also require some more elaboration of fire simulation data concerning when conditions become intolerable for the fire patrol.

If a very large fire would occur, several fire brigades could be needed to suppress the fire. Hostikka et al. (2012b) and Kling et al. (2013) have studied a tank wagon fire, where the goal was to assess the possibility of the fire brigade to get the situation under control in case of a major fire of flammable liquid leaking from a tank wagon in tunnel-like circumstances in a city centre. A successful suppression of major fires requires that there are enough resources (staff, equipment, water) in use and that the resources are available fast enough. The stochastic operation time modelling was used to study how long it takes that the suppression and cooling resources are available. The result of the simulation was the chronological distribution of the operational readiness of water cannons. The planned deck structure was located in the so-called first risk area; so the first rescue unit has to reach the target within six minutes of an alarm as a rule and an attempt is made to get the rescue team to the target within 20 minutes. An extended alarm will be given to the rescue platoon or company if it appears that the rescue unit is not enough for the task (Figure 16).

Because the objective was the simulation of the accumulating resources and because the critical resources were the water cannons, each water cannon was processed as a separate actor, who has its own timeline. The resulting distributions of water cannon arrival times are presented in Figure 17. This type of simulation of arrival times of multiple water cannons could well be implemented in FinPSA scripts and included in a fire PRA model. The time when a certain number of water cannons have arrived could be determined in the simulations to determine when a certain suppression level can be attained. Impact of a certain number of water cannons on the fire progression would require corresponding fire simulations. The simulations are also needed to determine how many water cannons are needed to control that fire. However, even a smaller number of water cannons can be used for cooling and preventing the fire from spreading. To model that kind of impact in the fire PRA model would likely require some simplifications, or fire simulations should be performed for all realisations of the operation time simulations.

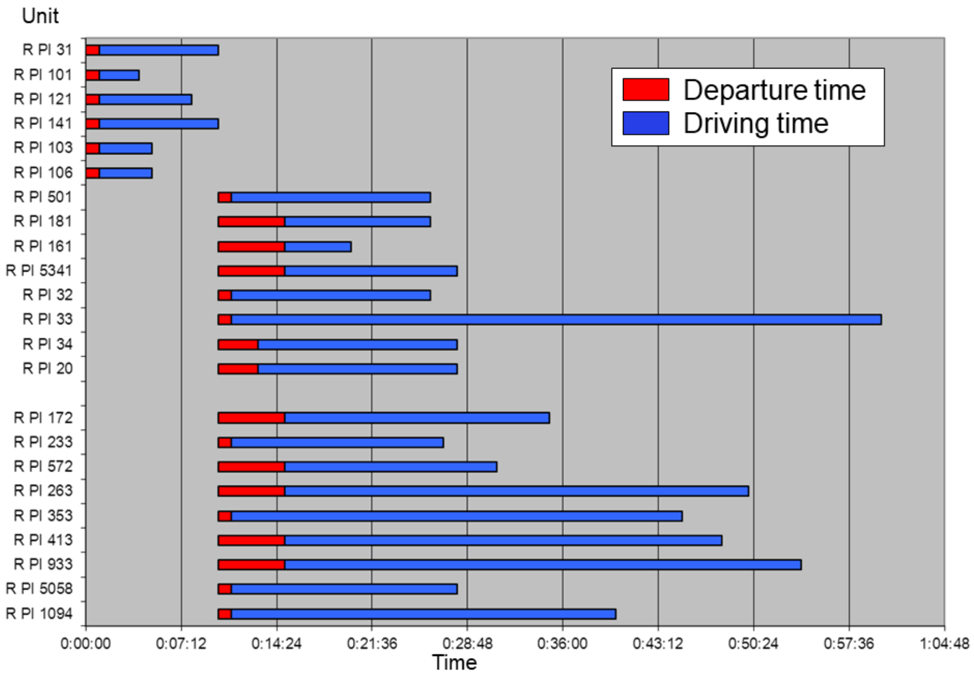

Figure 16. A diagram describing a situation of a major fire, where only one team is initially alerted to the target, but the alarm is later extended to the company plus tank trucks, a dangerous goods container and a high-power pump.

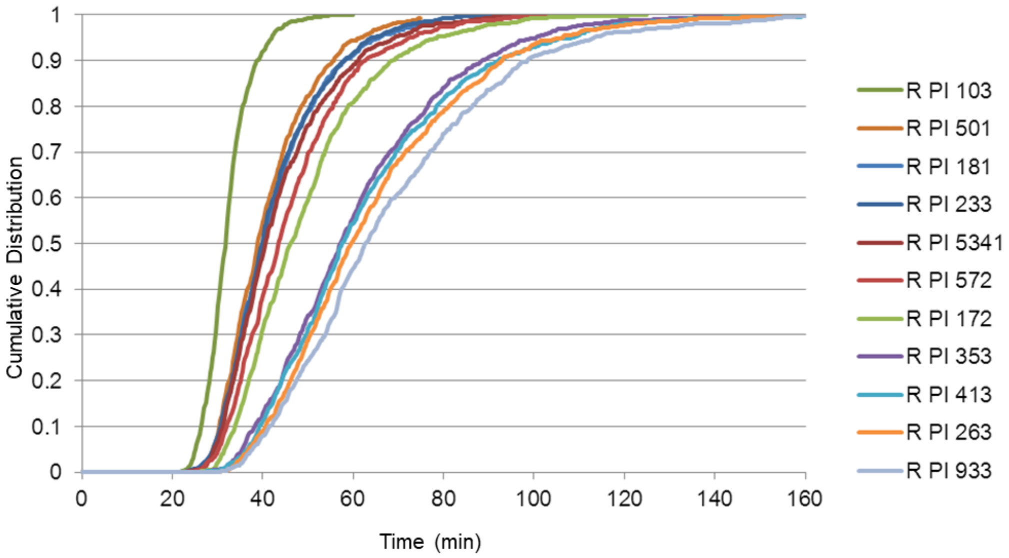

Figure 17. The resulting distributions of water cannon arrival times.

8. Summary and conclusions

Simulation-based event trees of FinPSA have previously mainly been applied to level 2 PRA, but as the method is more generally applicable, they are used to model fire scenarios in this task. The work was started, in 2019, by implementing a previous case study concerning simulation of fire behaviour and human operations in Olkiluoto cable room fire scenario in FinPSA. Originally, the analyses were performed by Monte Carlo simulations that combined fire simulations by FDS (McGrattan, 2013) and stochastic operation time simulations of firefighting operations. The purpose was to study the possibilities to prevent the consequences of a fire, before components start to fail causing failure of safety systems. In 2019, the same scenario was modelled using FinPSA, which proved to be an excellent tool for this purpose.

During 2020, we continued the case study and focused on the following topics:

- Dependencies between fire brigade actions and fire progression
- Reliability analysis of sprinkler systems
- Identification of uncertainties
- Extending the approach to a wider range of fire scenarios

Dependencies between fire brigade actions and fire progression have been explored further. Fire brigade may not be able to enter the room because of lost visibility or too high temperature. However, the visibility has only small impact on the cable failure probability, and the model is not sensitive to the assumptions made about the visibility. The time when the temperature becomes too high for fire brigade is quite sensitive to assumptions, but the cable has already failed at that point anyway. No needs to change the fire PRA model were identified based on the analysis.

A large number of uncertainties were identified for the cable room fire PRA study. The uncertainties were related to fire simulation parameters, interpretation of fire simulation results, fire simulation model itself, computation methods, time delays of firefighting actions and reliability of the automatic suppression system. The significances of different uncertainties were assessed according to possibilities. Most of the uncertainties were assessed to have a small significance for the results. The most significant uncertainties are related to some fire simulation parameters (particularly time of maximum heat release rate), reliability of the automatic suppression system and some central firefighting actions. Uncertainties related to the fire simulation model, its completeness and the computation methods may also be significant, but they are difficult to analyse. All in all, uncertainty analysis is a challenging, but important area that requires further considerations.

Reliability analysis of sprinkler systems was studied by reviewing previous analyses found in the literature and conducting a simplified fault tree analysis for a generic wet pipe system. Such reliability analyses have been quite rare or at least not published, and data related to sprinkler component failures are scarce. The fault tree analysis showed that the probability of simultaneous failure of three fire water pumps is small, but sprinkler components, such as wet alarm valve, can have larger failure probabilities. Collection of sufficient amount of failure data for sprinkler system components is necessary for credible reliability analysis. In additions, other types of failures, like manual intervention, design fault, and system being shutdown, should not be overlooked as those are quite common reasons for sprinkler system failures.

Some new modelling issues were considered from the point of view of FinPSA modelling. Modelling of multiple consequences, such as multiple cable failures, is relatively straightforward as demonstrated by a simple modelling example. Multiple fire brigades could also well be incorporated to the operation time model given that sufficient information about time delays exist. In addition, fire spreading outside the room could be included in the analysis, though it would require some more research to develop the detailed modelling approach.

References

Boneham, P., Georgiev, G., Guymer, P. (2019). An approach to fire probabilistic risk assessment modeling, uncertainty quantification and sensitivity analysis. PSA 2019, Charleston, SC, 28 April - 3 May, 2019.

Dodge, Y. (2008). The concise encyclopedia of statistics. Springer, New York.

Electric Power Research Institute, U.S. Nuclear Regulatory Commission. (2005). Fire PRA methodology for nuclear power facilities, Volume 2: Detailed methodology, NUREG/CR-6850. Palo Alto, CA, USA.

Frank, K., Gravestock, N., Spearpoint, M., Fleischmann, C. (2013). A review of sprinkler system effectiveness studies. Fire Science Reviews, 2:6.

Hall, J.R. Jr. (2010). U.S. Experience with sprinklers and other automatic fire extinguishing equipment. National Fire Protection Association.

Hall, J.R. Jr. (2013). U.S. Experience with sprinklers. National Fire Protection Association.

Hostikka, S. (2008). Development of fire simulation models for radioactive heat transfer and probabilistic risk assessment [doctoral dissertation], VTT publication 683. VTT Technical Research Centre of Finland Ltd, Espoo.

Hostikka, S., Keski-Rahkonen, O. (2003). Probabilistic simulation of fire scenarios. Nuclear Engineering and Design, 224, 301-311.

Hostikka, S., Kling, T., Paajanen, A. (2012a). Simulation of fire behaviour and human operations using a new stochastic operation time model. 11th International probabilistic safety assessment and management conference & the annual European safety and reliability conference (PSAM11 & ESREL 2012), Helsinki, 25-29 June, 2012.

Hostikka, S., Kling, T., Vaari, J., Rinne, T. & Ketola, J. (2012b). Pelastustoimen vasteen simulointi suurpalossa SIREENI-projektin tulokset. Espoo 2012. VTT Technology 61. 77 s. + liitt. 13 s.

Jyrkama, M.I., Pandey, M.D. (2016). On the separation of aleatory and epistemic uncertainties in probabilistic assessments. Nuclear Engineering and Design, 303, 68-74.

Kling, T. (2010). Palo-HRA - Operatiivisen toiminnan malli ydinvoimalaitosten paloriskien todennäköisyyspohjaiseen arviointiin, Versio 2, VTT-R-07211-10. VTT Technical Research Centre of Finland Ltd, Espoo.

Kling, T., Hostikka, S., Rinne, T., Vaari, J. & Hakkarainen, T. (2013). Stochastic operation time modelling of rescue situations. Conference Proceedings Interflam 2013. 13th International Fire Science & Engineering Conference. Royal Holloway College. University of London, UK. 24−26th June 2013.

Kloos, M., Peschke, J., Forell, B. (2014). Insights from and Integrated Deterministic Probabilistic Safety Analysis (IDPSA) of a Fire Scenario. Probabilistic Safety Assessment and Management PSAM 12, Honolulu, Hawaii, June, 2014.

McGrattan, K., McDermott, R., Weinschenk, C., Overholt, K., Hostikka, S., Floyd, J. (2013). Fire Dynamics Simulator User’s Guide, Sixth edition. National Institute of Standards and Technology, Gaithersburg, MD, NIST special publication 1019.

Moinuddin, K.A.M., Thomas, I.R. (2014). Reliability of sprinkler system in Australian high rise office buildings. Fire Safety Journal, 63, 52-68.

Nieminen, M. (2018). Rakennusten automaattisten sprinklerilaitteistojen luotettavuus [Master’s thesis]. Tampere University of Technology, Tampere.

OECD. (2015). International workshop on fire probabilistic risk assessment (PRA), NEA/CSNI/R(2015)12. OECD Nuclear Energy Agency, Paris.

Paajanen, A., Kling, T. (2013). Fire defence-in-depth assessment in TVO cable room − feasibility study, VTT-R-01072-13. VTT Technical Research Centre of Finland Ltd, Espoo.

Paudel, D., Hostikka, S. (2019). Propagation of model uncertainty in the stochastic simulations of a compartment fire. Fire Technology, 55, 2027-2054.

Rönty, V., Keski-Rahkonen, O., Hassinen, J.-P. (2004). Reliability of sprinkler systems, Exploration and analysis of data from nuclear and non-nuclear installations, VTT working papers 15. VTT Technical Research Centre of Finland, Espoo.

Sakurahara, T., Mohaghegh, Z., Reihani, S.A., Kee, E., Brandyberry, M., Rodgers, S. (2018). An integrated methodology for spatio-temporal incorporation of underlying failure mechanisms into fire probabilistic risk assessment of nuclear power plants. Reliability Engineering and System Safety, 169, 242-257.

Sakurahara, T., Reihani, S.A., Mohaghegh, Z., Brandyberry, M., Kee, E., Johnson, D., Rodgers, S., Billings, A. (2014). Developing a New Fire PRA Framework by Integrating Probabilistic Risk Assessment with a Fire Simulation Module. Probabilistic Safety Assessment and Management PSAM 12, Honolulu, Hawaii, June, 2014.

Siu, N., Sancaktar, S. (2015). Fire PRA Maturity and Realism: A Technical Evaluation and Questions, International Workshop on Fire Probabilistic Risk Assessment (PRA), NEA/CSNI/R (2015)12. OECD Nuclear Energy Agency, Paris.

TUD Office. (2015). T-Book, Reliability data of component in Nordic nuclear power plants, 8th edition.

Tyrväinen, T., Karanta, I. (2019). Dynamic containment event tree modelling techniques and uncertainty analysis, VTT-R-06892-18. VTT Technical Research Centre of Finland Ltd, Espoo.

Tyrväinen, T., Kling, T., Korhonen, T. (2020). Analysis of cable fire scenario with simulation-based event tree, VTT-R-01302-19. VTT Technical Research Centre of Finland Ltd, Espoo.

Tyrväinen, T., Silvonen, T., Mätäsniemi, T. (2016). Computing source terms with dynamic containment event trees. 13th International conference on probabilistic safety assessment and management (PSAM13), Seoul, Korea, 2-7 October, 2016.

U.S. Nuclear Regulatory Commission. (2016a). CCF parameter estimations 2015.

U.S. Nuclear Regulatory Commission. (2016b). Summary of SPAR component unreliability data and results, 2015 parameter estimation update.

VTT Technical Research Centre of Finland Ltd (2020). FinPSA – Tool for promoting safety and reliability. https://www.simulationstore.com/finpsa (link accessed 4.1.2021)