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Analysis of the Schiphol Cell Complex fire using a Bayesian belief net based model

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ABSTRACT

In the night of the 26 and 27 October 2005, a fire broke out in the K-Wing of the Schiphol Cell Complex near Amsterdam. Eleven of 43 occupants of this wing died due to smoke inhalation. The Dutch Safety Board analysed the fire and released a report 1 year later. This article presents how a probabilistic model based on Bayesian networks can be used to analyse such a fire. The paper emphasises the usefulness of the model for this analysis. In additional it discusses the applicability for prioritisation of the recommendations such as those posed by the investigation board for the improvements of fire safety in special buildings. The big advantage of the model is that it can be used not only for fire analyses after accidents, but also prior to the accident, for example in the design phase of the building, to estimate the outcome of a possible fire given different possible scenarios. This contribution shows that if such a model was used before the fire occurred the number of fatalities would have not come as a surprise, since the model predicts a larger percentage of people dying than happened in the real fire.

1. Introduction

In the night of the 26 and 27 October 2005, a fire broke out in the K-Wing of the detention centre of Amsterdam Schiphol airport [1].[1] The fire started soon after midnight in one of the cells and led to 11 deaths among the 43 cell occupants present in K-Wing at the time of the fire. The analysis of the fire was conducted by the Dutch Safety Board (Onderzoeksraad Voor Veiligheid, OVV) and released to the public 1 year after the accident [1].

Using the available information found in this report, the fire in the Schiphol Cell Complex is analysed using a model based on Bayesian Belief Nets [3]. The model estimates the extent of a fire in a building expressed in terms of percentage of people who die in that fire. The Bayesian Belief Network (BBN) [4,5] method is a probabilistic approach which represents the system variables by nodes and the influences between variables by directed arcs. One of the big advantages of this probabilistic method compared to traditional risk analysis methods such as Fault Trees and Event Trees is that, when additional information about some of the variables is available, it can be propagated through the network and the changes in the distribution of other variables can be studied.

The paper emphasises the big advantages of a model based on the BBN approach. Such a model can be used not only post-accident, for accident investigation, as Fault Trees and Event Trees are usually used, but also prior to an accident, to test scenarios and to choose the best option for reducing human damage in case of a fire in a building. This characteristic allows the application of the model at all the stages of the design process, from planning, and execution, through use. Moreover, after an accident, one can check how normal or expected the outcome of that fire was, given the particular conditions of that building and whether the damage could have been foreseen. This can be done not only based on a particular accident, but also in a more generic way, to determine the probability of occurrence of such an accident in a certain type of building or in a building having certain characteristics, in order to take measures and to reduce the probability of occurrence of the same accident in other similar buildings. Possible recommendations for avoiding such accidents in the future can be tested and the best one, if needed, can be chosen. A similar application of a model based on BBNs in the field of aviation safety can be found in [6].

The general model based on BBN method, called Human Damage in Building Fire Model (HDBFM), is applied in this paper to the Schiphol Cell Complex fire. Details on how the model was built up are described in Section 4. The information about the fire and the conditions at the place of the fire found in the accident report and presented in Sections 2 and 3 of the paper are included in the model and the updated distribution of the outcome of a fire in similar conditions is computed. The model results are compared with the actual outcome of the real fire and a conclusion regarding how

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[1] A translation of the report is available [2] The Dutch Safety Board. Fire at the detention centre Schiphol Oost. 2005. This article used the information from the original Dutch version.

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expected the fire was can be drawn. Moreover, different alternatives of measures proposed by the investigation committee can be tested and the best one can be chosen.

2. The Schiphol Cell Complex

At the terrain of Amsterdam Schiphol Airport a prison was in use for ordinary police duties, for drug users and for the temporary detention of aliens. In total 412 people could be held in the entire cell complex. The full complex consists of multiple buildings. The necessary details are explained only for the main building, which partly caught fire. A more extensive description can be found in the report of the Dutch Safety Board [1]. The main building included multiple wings, which are connected via a central corridor. Ten of such wings contained cells in which people were locked in. The K-Wing in which the fire started (see Fig. 1) was located in the far right corner of the central corridor with respect to the staff offices. The exit, shown on the left in the figure, leads into the central corridor. The emergency exit at the right-hand side of the figure leads to outside the building and therefore it was locked. The reason for this was the specific use of the building, namely a prison from which the cell occupants should not leave. The keys to this and other emergency exits are available to a limited number of guards on duty, but none of the guards initially responsible for the rescue in K-Wing.

The K-Wing is one fire compartment of in total around 850 m^2. The K-Wing had a length of 50 m in which 26 cells (former see containers) are located. The complex did not comply with the Dutch construction legislation on the maximum compartment area (500 m^2) and maximum walking distance from a cell (22.5 m). Regarding the emergency exits, the Dutch legislation (Building Decree [7]) defines an emergency exit in a prison as an exit leading to another smoke free compartment. Therefore, although Fig. 1 shows that the K-Wing of the Schiphol Cell Complex had two exits, only the one from the left end of the wing was considered an emergency exit and was used as such. The exit from the right end of the wing, although leading to open area, was not considered an emergency exit. This is because the outdoor area was enclosed by fences, and, according to the Dutch legislation, only if an exit can lead freely to a public outdoor area it can be considered an emergency exit. The information about using only one exit in emergency evacuation was used as base case in this analysis, but the case with two exits was also analysed to see if it produces considerable changes in the outcome of the fire.

A shell construction is built around the cells, leaving wasted space above the containers. The cells could be occupied by maximum two persons, thus 52 in total in the K-Wing. There is no central unlocking system for the doors. Consequently, the doors of the cells have to be opened and closed manually by the personnel. In the wasted space above the cells a dry sprinkler installation is installed. In case of a fire, this system can be linked to a water source by the fire brigade. Consequently, the sprinkler system can operate only after the arrival of the fire fighting services. Since in this case the fire fighting services arrived late, the sprinkler system is not considered in the analysis of the fire presented in this paper. The entire complex is equipped with a fire alarm system. Automatic fire sensors are placed in each cell. Moreover a manual fire alarm is located in the central area in the wings and at team stations (rooms for the guards).

3. The fire

At the night of the fire in total 298 people were occupying the cells in the Schiphol Cell Complex. 43 of them, aliens, were located in the K-Wing. At 23:55 a fire was detected in the K-Wing. The fire originated from cell 11 in the K-Wing, which was occupied by one person. The exact time the fire started is unknown. In this article the time it took before the fire was detected has been estimated based on simulation studies performed for fire investigation by the Dutch Safety Board (see [1], Appendix 4). Within 2 min (at 23:56:12) two guards arrived at the door of the K-Wing from the central corridor. After opening the door to the K-Wing, they first checked cell 3 before opening cell 11. One of the guards present waited with the occupant of that cell in the central hall (hence outside the fire compartment), while the second guard and a third guard, who had arrived in the meantime, started to open the other cells. When the smoke became too dense, these two guards stopped opening the doors and ran outside. They managed to open all cells but 9, 10, 12, 13 and 14. The exact moment the guards stopped evacuating the cells in the K-Wing is unknown. This is somewhere around midnight. Therefore, the total number of people in the fire compartment (K-Wing), relevant for our analysis, is equal to the number of prisoners plus the three guards who assisted the evacuation process, hence in total 46 people.

The emergency exit at the right end in Fig. 1 has been opened from the outside; however nobody was rescued via this door. It can be learned from the report of the Dutch Safety Board states that is took until approximately 0:21 (so 26 min after the detection of the fire) until the fire brigade's first attempt to get into the K-Wing. This attempt failed. The second attempt was taken at 0:30 (35 min after fire detection) in which the first three cells were checked. From Appendix 2 of the accident report we learn, that all remaining 11 cell occupants in the K-Wing had died by that time. In the subsequent events until the fire was considered under control at 2:55:05 and later completely extinguished no other lives were lost.

4. The model

The Human Damage in Building Fire Model (HDBFM) was developed as part of a Ph.D. research [3]. The main goal of the

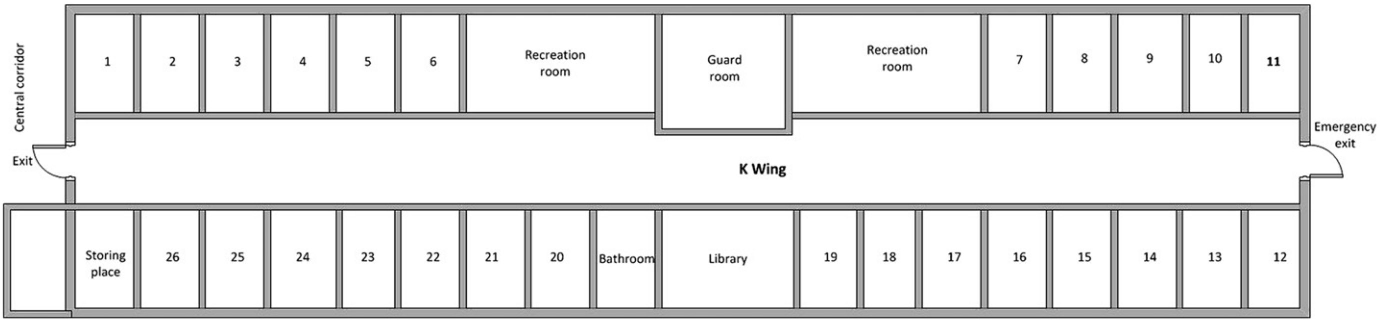

Fig. 1. K wing of Schiphol Cell Complex.

research was to integrate the three most important sub-systems of a fire in a building, the fire development, the people evacuation and the fire fighting actions, and to simulate the interactions between these sub-systems. The resulting model can be used for estimating the percentage of deaths in fire in a general building but also in buildings with particular characteristics. The model can be used at different stages of the design process of a building, as a decision tool which can help to compare alternatives and to choose those which have higher probability of smaller fire damage in terms of people being killed. The model is based on the probabilistic method called Bayesian Belief Nets.

4.1. BBNs—general presentation

The Bayesian Belief Networks have been applied successfully in the last several years in a large range of applications. Only in the area of dependability, risk analysis and maintenance, a recent review [8] found more than 200 papers between 1990 and 2008, with a considerably increase after 2000. Basically, a BBN is defined by a qualitative part and a quantitative part [4,5,9]. The qualitative part consists of a set of nodes which represent the system variables, and a set of directed arcs between variables, representing the dependencies or the cause–effect relations between variables. The quantitative part consists of conditional probability distributions for each node, given the states of the influencing nodes (also called *parent nodes*). Together, the quantitative and qualitative parts encode all the relevant information about the system variables and their interrelations, which, mathematically, means the joint distribution of these variables. The conditional independencies which are represented in the network by a missing arc between variables allow the decomposition of the joint distribution in a product of conditional probability distributions. In this way, instead of working with a large joint probability distribution, one can work with smaller pieces of it, but preserving the overall component interaction within the system. BBNs provide a useful tool to deal with uncertainty and with information from different sources, such as expert judgment, observable information or experience. Moreover, BBNs can solve some of the problems occurring with the classical risk analysis methods, especially the one related to common causes and human influence [10].

The first form of BBNs and the one which is still most used all over the world is discrete BBNs, which included only discrete variables, having a finite and usually a small number of states [4,5]. For nodes which have no influencing arcs, or nodes without parents, probabilities to take each of their values have to be specified in a simple probability table. For the nodes which are influenced by other variables, conditional probability tables (CPTs) have to be specified. A CPT includes the probability that the node takes each of its states, given all possible combinations of states of the influencing nodes. Although built on a solid theoretical base and showing appealing features due to relatively simple visualisation of complicated systems, discrete BBNs suffer from severe limitations when they are applied to real problems, especially due to the explosion of data needed for quantification [11,12]. Later on, the continuous Gaussian BBNs were developed, in which all the variables were assumed to follow normal distributions [9]. In this case, mean and standard deviations have to be specified for each node and a regression coefficient has to be assigned for each arc. The good news is that the number of inputs is considerably lower than in the case of discrete BBNs, but the bad news is that the regression coefficients are more difficult to be obtained from experts. Moreover, the assumption of normal distribution of all variables is a strong one and makes it impossible to use variables with another distribution. Combinations of discrete and normal variables were possible under certain restrictions [13].

The model used for the analysis in this article includes a new form of distributions: non-parametric BBNs [14], which allow both discrete and continuous variables, called probabilistic nodes. The influences between variables are expressed in terms of rank correlations, which show the strength of monotone association between ordered values of two variables. Moreover, the new form of BBN can also accommodate nodes which are expressed as functions of other nodes, for example, moving time, which can be expressed as an analytical function of waiting time at exits, distance to exit and walking speed. The simulation of the model is made using UNINET, a software developed at the Mathematics Department at Delft University of Technology under the CATS project [15]. The non-parametric BBNs are a rather young method, but have been applied already in several real-word problems, such as air transportation safety [15], risk–benefit analysis of food consumption [16], air pollution [17], dam safety [18], permeability field estimation [19] and bridge safety under traffic load [20].

4.2. Building up the BBN model

The main steps in building a non-parametric BBN are defining the graphical structure, in which the nodes and the arcs between them are drawn, assigning marginal distributions for each node and rank correlations for each arc. When data is available, both marginal distributions and rank correlations can be derived from data [14]. However, in many cases the data is missing or incomplete. In this case, structured expert judgment can be used for marginal distributions [21], but also for deriving the rank correlations [18].

For building up the graphical structure of HDBFM, a literature review and discussions with experts in the field were performed in order to determine factors which influence the outcome of a fire in a building. The graphical structure from Fig. 2 was obtained. For quantifying the model, information about some of the marginal distributions functions were found in the literature (see Table 1). Functional nodes were obtained using analytical formula or differential equations (see Table 2). For the other nodes structured expert judgment [21] was used to derive probability distributions. In this expert judgment exercise a group of experts was asked to assign their uncertainty regarding a set of variables of interest, by specifying the 5th, 50th and 95th quantiles of probability distributions of those variables. Then, using weights computed based on experts' performance on a set of seed variables, experts' opinion are combined and one distribution probability is obtained for each variable of interest. For arcs that are associated with rank correlations, the same structured expert judgment exercises was used to obtain conditional probabilities which then, are transformed into rank correlations [22]. The quantification of arcs which are directed to a functional node is specified by the functional relations associated with these nodes. The results of the expert judgment exercises as well as some discussions on these results are presented in [3,23].

4.3. Use of the BBN model

The main use of a BBN model is to make inference when new information about some of the variables is available. This means, in fact, that the conditional distributions are determined, given the available information. The information can be propagated through the network in any direction and changes on all the other variables can be obtained. This feature is important when one wants to see how the situation is changed in a particular case, given particular conditions. Different from other methods, such as Fault Tree, when a new model has to be built up for each new situation, the BBN methods allow automatical update. This makes it a very general model to be applicable for particular cases in

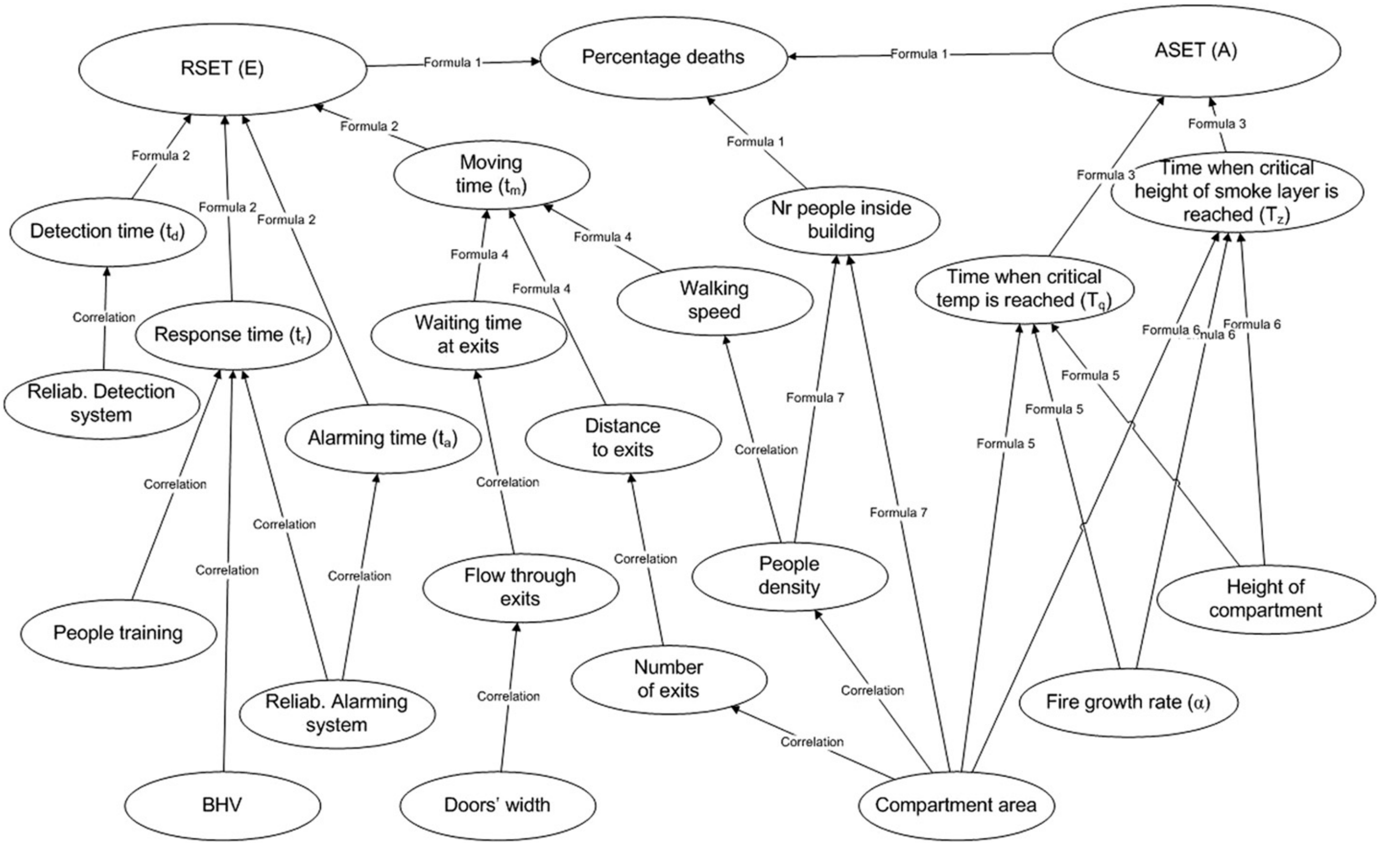

Fig. 2. Human damage in building fire model.

Table 1
Variables for which marginal distributions are taken from literature.

	Name	Description	Distribution	Source/reference
1	DetTime	The time interval from ignition until the fire is detected	Log-normal (600,300) s	[25]
2	AlarmTime	The interval of time from the detection of the fire until the population is alarmed	Log-normal (132 156) s	[26]
3	RespTime	Time interval from the moment when the population is alarmed until when the people start to move through the exits	Log-normal (130,120) s	[25]
4	Doors'Width	The door's width (m)	Uniform [0.9; 1.6] m	[25]
5	WalkSpeed	Individual walking speed (m/s)	Uniform [0.8; 1.7] m/s	[27]
6	FireGrRate	Characteristic of the fire intensity (kW/s^2)	Triangular (0.027; 0.04689; 0.101) kW/s^2 OR: Uniform [0.01;0.1] kW/s^2	[28] [25]
7	HeightComp	Compartment height (m)	Uniform [2;12] m	[25]

Table 2
Functional nodes.

	Name	Description	Formula
1	MoveTime	Moving time is the time interval from the moment when people start to move through an exit until a safe place is reached	MoveTime = WaitTime + DistExit/WalkSpeed
2	RSET	Required Safety Egress Time is the time needed by people to reach a safety place measured from the ignition of the fire	ASET = DetTime + AlarmTime + RespTime + MoveTime
3	N	Number of people inside the building at the moment when the fire starts	N = PplDens∗CompArea
4	TcTemp	Time when critical temperature (here 373.5 °K) is reached	[29,30]
5	TcSmoke	Time when critical height of the smoke layer (here 2.1 m) is reached	[29,30]
6	ASET	Available Safety Egress Time is the time until the critical conditions are reached inside the building	ASET = min(TcTemp, TcSmoke)

which some of the parameters are known. However, even in such particular cases there are uncertainties about part of the variables and the outcome of the model expresses these uncertainties. Therefore, the outcome of the model is the probability distribution function of one or more variables of interest, in this case the percentage of dead people in the building.

Therefore, comparing two or more cases means in fact comparing the probability distribution functions for percentage of deaths in these cases. There are more options for comparing two probability distributions. One of them, and the most used, is to compare the mean values. Although this is the easiest way, the average value of a random variable does not always contain all the information, especially in the case of an accident leading to a disaster. To have more information, the variance of the variable also has to be included. There are, however, cases, in which a high or a small percentile, or even the minimum and maximum of the estimated value are important. For example, it could be important to have a certain small probability that the percentile of deaths is above 95%. Or it can be important to compare the medians of two probability distributions. Examples of all these comparisons will be given in the following sections.

5. Application to the Schiphol Cell Complex fire

In order to apply the HDBFM Model to the Schiphol Cell Complex fire, the fire report was analysed and the values for the variables included in the network were derived. Since the model is built for a fire compartment, the analysis and thus the values of the factors discussed only refer to the K-Wing.

For some of the variables, clear information was found in the report, but for most of them, the real values have to be inferred from other information. Based on the data presented in the report, the model variables can be divided in three categories:

- Factors for which fixed values are specified in the report (e.g., size of the compartment, number of people inside the building).
- Factors for which approximated or alternative values can be derived from the information presented in the report. This category includes also the possible values according to the recommendations made by the investigation team to improve the safety of the building.
- Factors for which no information is available; these factors remain unknown, following the associated probability distributions.

The values set for factors in the model are discussed per category in the following sections.

5.1. Fixed values specified in the report

Besides the fixed values for the *compartment area* (850 m^2) and *height of the compartment* (2.4 m) the accident report also provides certain information for four other factors (see Table 3): *waiting time at exits*, *number of people inside the building*, *density of people* and *percentage of deaths*. The values for these four factors, although not specified directly in the report, can be derived easily from the information found. Discussions about how they are inferred are presented in this sub-section.

Waiting time at exits is a random variable that is important when there is a large number of people inside the building who start to evacuate and reach the exits at about the same time, resulting in a queue at the exits. Given the fact that in the Schiphol Cell Complex the guard opened each of the doors one by one, so, consequently, people had time to exit the compartment without forming queues, it is reasonable to assume that there was no waiting time at exits. Moreover, in the report there is no indication of queuing forming at the exit of the K-Wing.

One can argue the *number of people* inside the K-Wing. In total 43 people were imprisoned: one in the cell where the fire started, 31 people who were saved and 11 people who lost their lives. In the analysis, it is assumed that apart from the imprisoned people all three guards who assisted in the evacuation were relevant people in the wing as well. Therefore, the total number of people is 46. This number was also used to compute the people density, the BHV percentage and the percentage of deaths.

The *people density* inside the building is difficult to estimate in real cases. It depends entirely on the location of the people at the time when the fire starts. However, given the fact that the building was a prison and the fire started at night, when all the people were in their own cell, it can be considered that they were uniformly distributed over the surface of the compartment. Therefore, a fixed value for people density (0.054 people/m^2) is obtained by dividing the number of people in the building (46) by the surface of the compartment (850 m^2).

The number of people killed in the fire is specified in the report as being equal to 11. Knowing the total number of people in the building (46), it is straightforward to derive the outcome of the fire, measured as the *percentage of people* killed: $11/46=0.239$ or 23.9%.

5.2. Approximated or alternative values based on assumptions or recommendations

Using information in the accident report made it possible to approximate values or set an alternative distribution for 6 of the factors (see Table 4). Some of them, although specified in the report, are based on assumptions and therefore not considered in the previous category fixed values.

Distance to exit is in general difficult to be specified in a given situation. It not only depends on the structure of the building, but also on the location of the people within the building and on their decisions regarding which path to follow to the exits. If needed, an estimation can be made based on the average, longest or minimum walking distance. In this analysis, the longest distance is considered. More precisely, the travel distance to exit is 54 m according to the accident investigation report, which equals the length of the whole corridor (45 m) plus the distance from the door of the cell to the middle of the corridor (6 m) multiplied by

Table 3
Values for model variables for which certain information derived from the accident report.

Factor/variable	Certain inform/value	Reference in accident report [1]
Compartment area	850 m^2	Note 312 on p. 108
Height of compartment	2.4 m	Note 172 on p. 70
Waiting time at exits	0	pp. 28–29
Number people inside the building	46	11 victims, 32 evacuated people and 3 guards
Density of people	0.054 ppl/m^2	46 people/850 m^2
Percentage of deaths	0.239	11 victims out of 46 people in the compartment

Table 4
Information for model variables which lead to approximated values or distributions.

Factor/variable	Value (first choice, as in the report)	Alternative or approximated values	Reference in accident report [1]	Remark on alternative or approximated values
BHV	0.02	0.065	p. 85	
Number of exits	1	2		Based on recommendation
Distance to exits	54	28 U[9;54]	Note 328 on p. 112	Based on recommendation or between minimum and maximum
Detection time	Unknown	79 s;109 s; 56 s	Appendix 4, pp. 232–234	Based on three real fire simulations
Time when critical height of the smoke layer is reached	Unknown	10 min+detection time	Appendix 2	
Alarm time	Unknown	12 s	p. 26	
Response time	Unknown	122 s	p. 29	Based on recommendations

1.5 (see [1], note 328 on p. 112). This means in fact that all people are assumed to be located in the cells at the end of the corridor. This assumption will give more pessimistic results, but leads probably to decisions which ensure with a higher probability a safer situation. Alternatively, for the maximum distance it is possible to restrict the interval of values for this random variable in the model and to consider that it is uniformly distributed between the minimum value (9 m) and the maximum value (54 m). Moreover, when the recommendation of the investigation team to use two exits is considered, the maximum distance is reduced to 28 m, as specified by the report.

By Dutch law, it is obligated to have people present in the building who are trained in case of necessary evacuation, called BHV[2] persons. According to the norms in the Dutch Occupational Health and Safety Act (Arbowetgeving) there should be at least one BHV person for every 50 people present in a public building, leading to the fixed value 0.02. However, since all guards at the Schiphol Cell Complex are in fact BHV trained, the factor can alternatively be set at the number of guards involved in the evacuation of the people present. This results in a value of 3/46=0.065. The analysis considers both values, but the value according to the regulations, 0.02, is set as a base.

By definition, the *detection time* is the time interval between the start of the fire and notification of the fire either automatic or notified by somebody. With almost all fires, the precise moment when the fire started is unknown. It can be estimated on the basis of the material on fire, the quantity of fuel in the compartment, the characteristics of the detection system and using (real or computer) simulations. In the investigations of Schiphol fire real simulations were used. Three scenarios were tested: two in which a cigarette was accidentally dropped on the foot end of the bed, the difference being in the way linens was placed on the bed, and one scenario in which the fire was started on purpose. The simulations resulted in three point estimates of detection time: 79, 109 and 56 s, respectively. These values will be used as fixed values for detection time in the cases presented in the next section.

Time when critical smoke layer is reached in a fire compartment is defined as the first instance when the smoke layer reaches the critical level. This moment is in general difficult to be estimated in a real fire, but a rough approximation can be made using the time when the first person died in that fire due to smoke inhalation, if known. The fact that other persons died later only has to do with their location inside the building or the fact that their resistance to the smoke inhalation is different. In the case of Schiphol Cell Complex fire, all the victims died as result of smoke inhalation. The first person died 10 min after the automatic fire alarm went off and the last person died 30 min after the alarm. Therefore, the *time when critical smoke layer is reached*, measured from the start of the fire, can be approximated as the sum of the detection time obtained from simulations and the time when the first person died. The values are presented in Table 4.

The accident report shows much information about the exact sequence of events after detection of the fire. This information helps to estimate the *alarm time*, which is the time between detection of the fire and the moment when people inside the building are informed about it. According to the information obtained from the report, the fire was detected automatically at 23:55:00 and at 23:55:12, the alarm is accepted by the centralist in one of the next wings of the cell complex. This centralist recognised the alarm correctly. However, due to the wrong coding, another centralist elsewhere at the cell complex after checking considered the alarm to be false. As a result, the fire was not recognised as such by the entire organisation immediate. After the correct location of the fire was found, actions are being taken.[3] Thus, it can be said that the first actions were taken 12 s after the detection of the fire, when the centralist accepted the alarm, but these actions were followed up different dependent on the location of the guards within the entire complex. Therefore, setting alarm time to 12 s is not considered as basic case, but rather as an alternative case, showing what would have happened if there was no misinterpretation of the coding.

The accident investigation team gave some recommendations for improving the safety of similar buildings in case of fire. From these recommendations, values for some of the factors of the model, such as response time and number of exits, can be derived.

One of recommendations refers to the emergency exits. As mentioned before, the layout of the K-Wing had two *exits*. However, for security reasons, the emergency exit to the outside of the K-Wing was locked with a key. Only a limited number of people, but none of the guards from the K-Wing present the night of the fire, had that key. As a consequence, only the exit from the left end of the corridor was used for evacuation of people. However, the investigation team recommended two emergency exits to be used in such situations. If both exits are used for evacuation, then the maximum *distance to the exits* should be set at 28 m.

The *response time* is the time taken by people to react to the alarm; it is thus the time between the alarm going off and people starting to move towards the exits. In general, this time is specific for each individual within the building, but average, minimum or maximum values can be used for approximations. The general definition has to

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[2] BHV, in Dutch Bedrijfs HulpVerleners, are employees with the duty to assist in case of emergencies in companies. These people get special training for rescue activities.

[3] In fact, in the case of the Schiphol Fire, the guards did not call the fire department. The fire department was alerted automatically 3 min after the acceptance of the fire alarm.

be modified for this particular fire. There are two categories of people in a prison: the prisoners and the guards. Both have to be evacuated to prevent victims. In the fire, the actions of the prisoners depend upon those of the guards. The guards had to open each of the cell doors. Therefore, the response time for each of the cell occupants starts at the moment when the door to his or her cell is opened. Since the cells were opened one after another, it would not be appropriate to assign the response time to the same fixed value for all prisoners. However, one of the recommendations of the investigation team was to install automatic systems for opening the doors, which means that in this case all the cell doors are opened, so all the prisoners start to move toward the exits at the same time. This would allow to set the response time to one fixed value. In the case of the Schiphol Cell Complex fire, this would be equal to the moment when the first door was opened, which, according to the fire report, is 122 s after the automatic fire alarm started. The situation with a fixed response time can be considered specific not only to cell complexes with automatic unlock system, but also to other type of buildings, for example schools, where the teacher has to allow the pupils to leave the room after which all of them start the evacuation at the same moment.

5.3. *Factors for which no information is available*

The accident report provided accurate information for 13 of the factors in the model. These factors are marked with grey blocks in Fig. 3. The other factors, for which no information is found in the report, the distributions of the functional relations from the original model were retained. In this section, it is discussed why no value or alternative distribution was set to the model for these factors.

The report states ([1], pp. 25–26) that both the detection and the alarm systems worked. However, this is not a reason to say that they were reliable, or that their reliability is equal to 1. The reliability of a technical component is tested in long runs, and equals the ratio between the number of times when it worked on demand (when it was required to work) and the total number of tests. For the *reliability of the detection system* and the *reliability of the alarm system*, certain specific values can only be set up if the type of system is known and if the specific type of system has been tested several times before. This information for the installation in the Schiphol Cell Complex is not available.

The *people training* factor refers to the number of days between evacuation exercises. In general, this is a commune characteristic of a building when it can be assumed that all the people from that building took part in the last evacuation exercise. For the Schiphol Cell Complex, the report contains information on an evacuation exercise that was organised on 12 February 2004 ([1], note 199 on p. 79), but it also mentions that none of the guards involved in the fire participated in that exercise. Moreover, the cell occupants were at the cell complex for a short stay. It is hard to give this factor a value, because the people inside the building do not stay long enough in that building to participate in evacuation exercises. The same applies to any public building, such as a faculty or a theatre. On the other hand, with an office building, a value for this factor can be found, which is at minimum one time per year, according to article 2.22 of the Dutch Labour Act on Health And Safety [24], assuming compliance.

The same applies to the *fire growth rate* variable. The fire growth rate could be estimated on the basis of the material that was on flame and the quality of fuel in the compartment. However, this estimation is very rough and, although a fixed value would decrease the uncertainty regarding the outcome of the fire, a bad approximation could lead to wrong decisions. It is, therefore, better to keep the variable uncertain instead of setting it at a wrong value (see [1], Appendix 4).

Fig. 2 shows that the outcome of a fire in terms of the percentage of death is determined by a functional relation between the factors ASET and RSET. Available Safety Egress Time (*ASET*) is the minimum time between the moment when the critical height of the smoke layer has been reached and the time

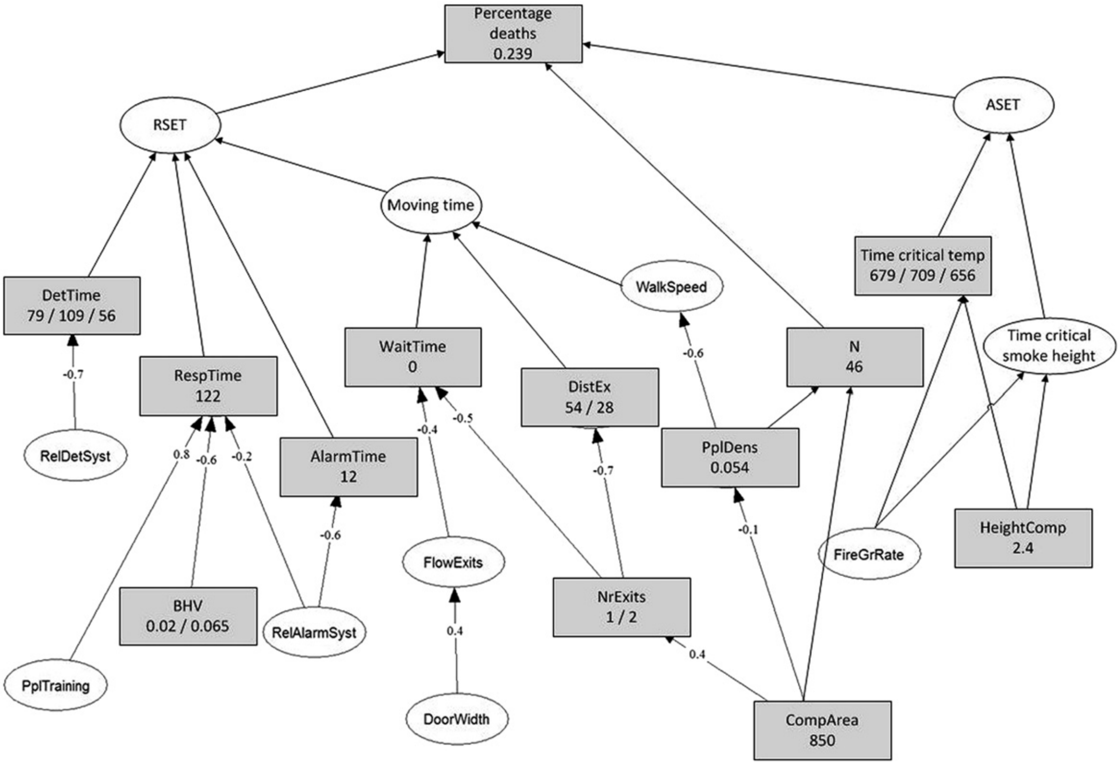

Fig. 3. Factors’ values provided in the accident report.

when a critical temperature is reached. No certain value is set, although it is said that all the victims died because of smoke inhalation, so the ASET should by its functional relation be equal to the time when the critical height of the smoke layer is reached. Rescue Safety Egress Time (*RSET*) is a characteristic of each individual inside the building. One fixed value for this variable means that all the people leave the building at the same time. This assumption is not true for this case, since two guards opened only one door at a time and guided each prisoner to the exit, so people were evacuated one by one. Therefore, the best option is to leave this variable uncertain.

Based on the information presented in Section 5, several cases were defined. These cases as well as the results of the simulations are presented in the next section.

6. Results

Based on the information found in the fire investigation report, a set of simulation cases can be defined. The information that is clear thus for which no assumption had to be made (see Section 5.1) defines the base case. The other cases are built up based on the approximated or recommended values. The modified values are in the bold cells in Table 5. All the factors that are not included in this table are kept uncertain, according to the model for the general case. The list of simulation cases and a short description for each of them are given below:

- *BaseCase*: factors for which clear information is found in the accident report.
- *Case1*: percentage of BHV people changed to alternative value, corresponding to the number of guards presented in the building at the moment of the fire.
- *Case21, Case22 and Case23*: values for detection time and time when critical smoke layer is reached are based on controlled fire simulations results presented by the investigation team.
- *Case3*: alarm time is fixed to the approximated value derived from the accident report.
- *Case4*: distance to the exit based on other distribution (instead of maximum distance).
- *CaseR1*: recommendation to use automatic unlock system.
- *CaseR2*: recommendation to use both exits of the wing.
- *CaseR3*: recommendation to use automatic unlock system and use of both exits (combining R1 and R2).

All these cases are simulated by setting the factors to fixed values and generating the conditional joint probability distribution of the other probabilistic nodes. The associated distributions for the functional nodes defined by complex equations, such as time when critical height of the smoke layer is reached, as well the other factors deriving from these are computed in Matlab, using the conditional joint distribution. Therefore, conditioning on a functional node can be done only by selecting from the joint distribution those samples which satisfy the imposed condition. For example, when the condition is set on the time when the critical height of the smoke layer is reached to be equal to one of the three values presented in Table 5, out of 100,000 unconditional samples, only about 100 satisfy the condition. This leads to a reduced number of conditional samples, which are not always sufficient to derive conclusions about the behaviour of the conditional factors. Therefore, conditioning on functional nodes is not possible using this method. For cases 21, 22 and 23, only conditions on the detection time are set. The resulting values for the time when critical height of the smoke layer is reached, are computed and compared with the corresponding values according to conditions.

For all cases, the percentage of deaths is equal to 0.239. Since this node is a functional node, it cannot be set to a fixed value. However, this value is compared to the average values of percentage of deaths obtained from simulations for each of the discussed cases.

One more case is introduced in the comparison: the case when none of the variables is assigned to fixed values, called general case (denoted GC), for which the average percentage of deaths equals 15.23%. This case corresponds to any fire conditions in any building with any occupancy; cases BC, C1, C4 and CR2 correspond to this particular building, with particular occupancy, but to any fire conditions; cases C21, C22, C23, C3, CR1 and CR3 correspond to this particular building, with this particular occupancy and these particular fire conditions. The relative changes in the mean and standard deviation of percentage of deaths for each of the cases described above comparing with the general case can be seen in Figs. 4 and 5. For each of these cases 10,000 samples were used.

It can be seen that for almost all cases, the average percentage of deaths is considerable higher than for the general case (see the bars in the negative area part of Fig. 4). However, it should be reminded that the model in the general case is built up for all kinds of buildings, in any conditions, while this particular fire is in a specific type of building, with specific restriction for evacuation and, therefore, the results should not be surprising. There are only three cases for which the average percentage of deaths is slightly reduced comparing with the general case: C21, C22 and C23. These are the cases corresponding to the condition set of detection time according to results of the controlled fire simulations. The aim of these simulations was to find the causes of the fire, whether it was an intentional or unintentional fire, and not to study the fire development and the critical times associated with it. Moreover, one should not forget that these cases are not only single estimates of a random variable, thus exposed to

Table 5
Simulation cases.

	Cases							
	BC	C1	C2	C3	C4	CR1	CR2	CR3
CompArea (m^2)	850	850	850	850	850	850	850	850
HeightComp (m)	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
NrExits	1	1	1	1	1	1	**2**	**2**
BHV	0.02	**0.065**	0.02	0.02	0.02	0.02	0.02	0.02
DistEx (m)	54	54	54	54	**~U[9;54]**	54	**28**	**28**
WaitTimeEx (s)	0	0	0	0	0	0	0	0
N	46	46	46	46	46	46	46	46
PplDens	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
DetTime (s)	–	–	**79/109/56**	–	–	–	–	–
Tc_smoke (s)	–	–	**679/709/656**	–	–	–	–	–
AlarmTime (s)	–	–	–	**12**	–	–	–	–
RespTime (s)	–	–	–	–	–	**122**	**–**	**122**

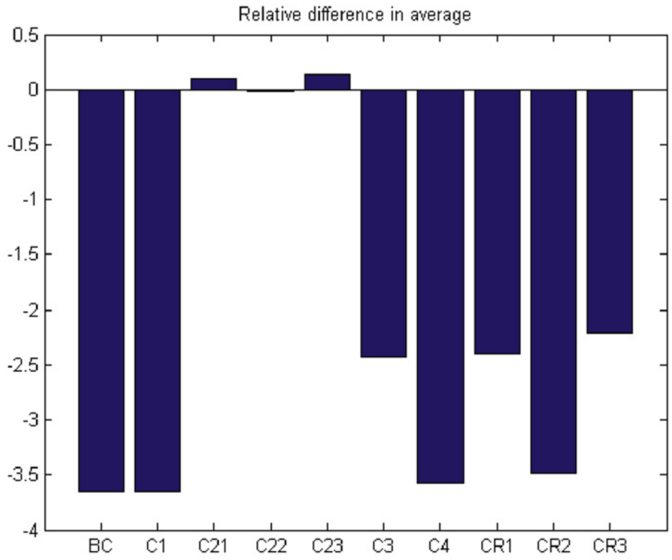

Fig. 4. Relative change in the mean of percentage of deaths for the simulation cases (comparing with the general case, for which average percentage of deaths is 15.24%).

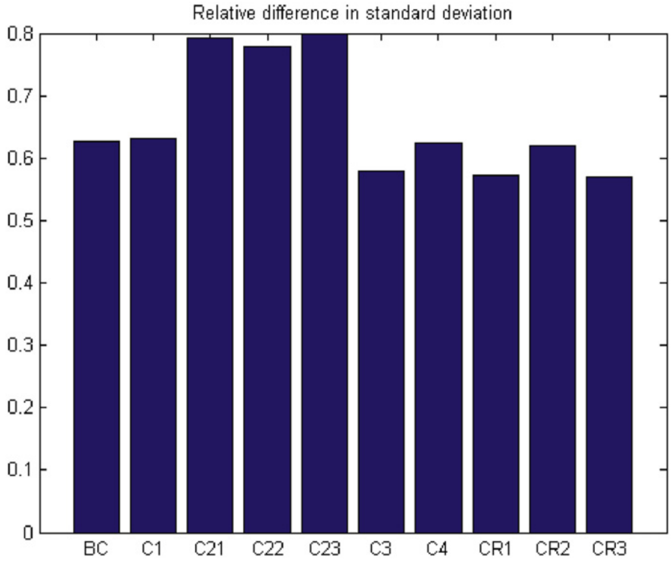

Fig. 5. Relative change in the standard deviation of percentage of deaths for the simulation cases (comparing with the general case, for which standard deviation of percentage of deaths is 28.72%).

uncertainty, but also that in these cases conditions have to be set on the time when critical height of the smoke layer is reached, according to the discussions in the previous section. Since this variable is a functional one, the conditioning is not possible. However, it can be checked what the average time is, when critical height of smoke layer is reached in these cases, as resulting from the conditional joint probability distribution. The values for the three cases are lower than they should be (see Table 4), which concludes that, indeed, the resulting percentage of deaths in these cases is optimistic.

Comparing the ten cases, it can be said that there is hardly any difference between cases BC and C1, which is expected, since the difference between 0.02 and 0.065 in the value for BHV is very small. It can also be noticed from Fig. 4 that cases C3 and CR1 produce almost the same change in the average outcome. However, the best cases, in the sense that it produces the lowest average percentage of deaths, are C3, CR1 and CR3. Among the three cases corresponding to the recommendations of the investigation team, the safer is the one which combines the two recommendations, CR3. However, using an automatic alarm system, which allows all cell doors to open at the same time (case CR1) is safer on average than using two exits for evacuation (case CR2).

Regarding the reduction of the standard deviation, it can be seen from Fig. 5 that when exact values are set to a fixed value, the model uncertainty of the percentage of deaths is reduced. This happens for all cases, with the highest relative reduction comparing to the general case for cases 21, 22 and 23.

Comparing the results of the simulations of the ten cases with the percentage of deaths in the real fire, it can be said that for all cases, there is a very small probability that the outcome would be lower than 0.239 (or 23.9% of deaths). As it can be seen in Fig. 6, there is around 75% chance that the percentage of deaths is lower than 0.239 in the general case, while this chance is considerably reduced for almost all the simulation cases presented in this paper. The chance to have an outcome lower than 23.9% of the number of people inside the building is almost zero for cases C3, CR1 and CR3. For cases BC, C1, C4 and CR2, the percentage of death people in building is always higher than 0.239. However, for cases C21, C22 and C23, there is a very high probability (over 90%) that the percentage of deaths is lower than the real outcome of the fire.

The fact that in almost all cases the average percentage of deaths is higher than the outcome of the fire (23.9%) is also suggested by the investigation team, which concluded that a fire compartment should not exceed 500 m^2. This seems to have an important influence on the outcome of the fire, together with the height of the compartment, which is also the conclusion of the sensitivity analysis study presented in Hanea [3].

7. Conclusions

The fire at the Schiphol Cell Complex on the night of 26 and 27 October 2005 was analysed using the Human Damage in Building Fire Model, which is based on Bayesian networks. The information on the factors included in the model was collected from the report of the investigation team and simulations were made using these values. Some recommendations suggested by the investigation team were also analysed.

The main goal of the paper was to show how the HDBFM can be applied to analyse a real fire and how the results of the model can be used to prioritise different alternatives. Although using only one fire it is difficult to say if the model produces a good prediction of the outcome, this model can be used to compare different alternatives or scenarios. Therefore, the numerical values of the model results are not used in their absolute value, but rather as means to compare alternative scenarios. A number of similar fires would be needed, so that the distribution of the real fire data can be obtained and compared with the outcome simulation. Since this is not possible until a structured collection of events is available, the thing that can be said with any certainty about the outcome of just one event is whether the building and occupancy characteristics increases the chance of a higher percentage of death people than in a general case. The results of the model can also be compared with the real outcome of the fire (23.9%) and the probability that the outcome of the fire would be less than this real value can be computed in some specific conditions. According to the simulation results presented in the previous section, the outcome of the fire in the Schiphol Cell Complex should not have come as a surprise to the authorities in most of the scenarios analysed, since the probability that the fire would end up with an outcome of less than 0.239 was very small. The only exception would have been if the detection time had been set at the values obtained from real simulations (Case21, Case22 and Case23); but one should take into account that

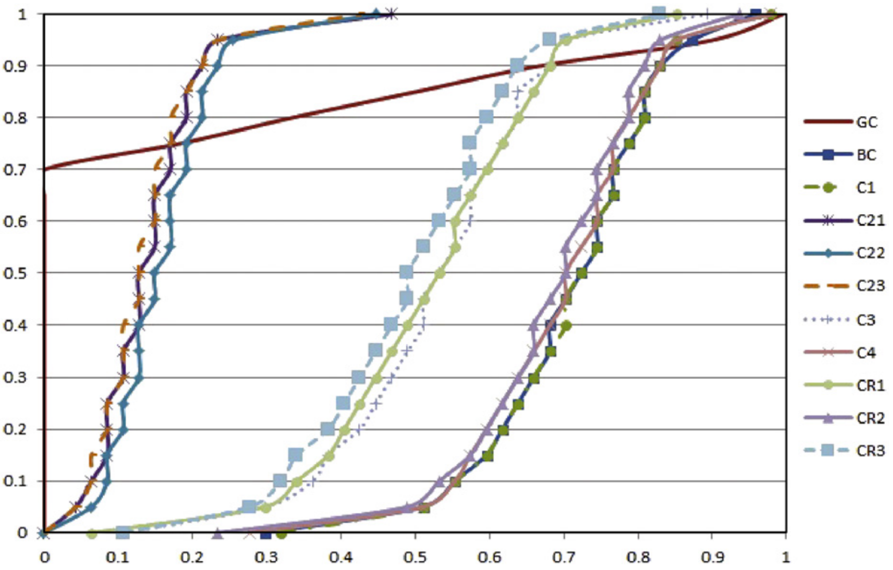

Fig. 6. Cumulative distribution function for percentage of deaths—all cases.

in these cases the values of the detection time were obtained from real simulations of the development of the fire in a cell, and that some of the conditions might not be the same as in the real fire.

The conclusion for most of the cases analysed in this paper is that the conditions of the fire at the Schiphol Cell Complex Fire had a very high chance to lead to outcomes higher than the actual fire outcome. From a statistical point of view, when the model result is situated at the tails of the probability distribution obtained when all the known parameters are fixed, one should reject the null hypothesis of correct model. Correct model means here that the outcomes of real fires follow the distribution given by model. However, according to the classical statistics, there is still 5% probability to reject the null hypothesis when it is true. Or, with other words, if 100 such real fires are analysed and for more than five of them the outcome is at the tails of the distributions given by model for those specific conditions, then one can say that the model does not produce a good estimation. On the other hand, if for less than five fires the real outcome is not at the tails of the distributions, one still cannot say anything about the model correctness.

Therefore, the main goal of this paper was not to validate the model, but to show how the model can be used to compare between different alternatives. In this way, the model provides a prioritisation of the recommendations for the improvements of the safety of the building. It can as such thus be used by the Dutch Safety Board, prison owners and building designers to learn from this incident and prevent accidents in similar conditions in the future. If one has to choose for only one change, the model can be applied. Moreover, the model can be used to check what are the most probable combinations of causes that lead to that outcome, by conditioning on different values of the influencing factors.

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