13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Probabilistic risk assessment of fire occurrence in residential buildings: Application to the Grenfell Tower

Hector Diego Estrada-Lugo
PhD student, Institute for Risk and Uncertainty, University of Liverpool, Liverpool, UK

Marco de Angelis
Postdoctoral Research Associate, Institute for Risk and Uncertainty, University of Liverpool, Liverpool, UK

Edoardo Patelli
Senior Lecturer, Institute for Risk and Uncertainty, University of Liverpool, Liverpool, UK

ABSTRACT: Fire occurrence is one of the most devastating events in residential buildings, among other civil engineered structures. The importance of providing mathematical tools that support fire risk assessments is imperative to improve fire containment measurements as well as accident prevention. In this paper, a novel probabilistic method based on credal networks is proposed to assess the impact on the expected risk of the variables involved in the cause and prevention of fire events. This approach can capture the epistemic uncertainty associated with data available in the form of the probability intervals. This helps to avoid hard assumptions based on the use of crisp probabilities that may lead to unrealistic results.
A general model is proposed and then adapted to the Grenfell Tower fire by introducing as evidence the specific conditions of the case study. Different fire scenarios are created to study the effects of the components involved in the accident. The probabilistic outcomes of those scenarios are used to compute the expected risk of unwanted factors, e.g., fatalities and fire costs as part of the fire risk assessment. Different data sources and experts have been consulted to enhance the accuracy and quality of the report.

1. INTRODUCTION

The Grenfell Tower fire that happened on 14 June 2017 left not only a large number of material losses but also, a fatal casualties toll of 72 and 70 physically injury cases, Macleod (2018). The impact in the demographics fatality risk was increased significantly in purpose-built blocks of flats higher than 10 storeys, i.e., buildings similar to the Grenfell Tower. In addition to that, the costs due to litigation, compensations of death or injured inhabitants as well as demolition and re-building costs sum up to £1 billion only for this case, Evans (2017). Such figures make the Tower fire one of the most expensive and most complex accidents reported by the Met Police in London, BBC NEWS (2018). This event has shown the vulnerability of such structures to fire that may lead to costly material loses as well as tragic casualties. The case of dwelling and purpose-built flats are of special importance as actions of inhabitants and conditions of appliances result in fire accidents and subsequent human and economic casualties. According to reports of the UK Home Office Fire Statistics, about 10 fatalities per 1000 accidental fires happened in dwelling appliances. This rate is three times higher than for other facilities such as hospitals, offices or shops, Home Office UK (2018). Furthermore, the costs associated with the losses due to fires in the UK sum up to £1.5 billion per annum, Matellini (2012).

In order to prevent, and reduce, tragedies like the one occurred at the Grenfell Tower in London, methods that take into account the complexity of the building structure and the factors of fire, as well as the uncertainty attached to those factors, are needed. Probabilistic tools like Fault Tree and Event Tree techniques have been often used to produce fire risk assessments, Khakzad et al. (2011). Such analysis tools can represent the dependencies of the factors that lead to the fire event in a quantitative logical and organised manner. However, some shortfalls must be noted, for instance, Fault Tree is not suitable for large systems, especially those that present common cause failures. More importantly, several events are assumed to be independent, which is rarely found in real systems.

Another probabilistic technique called Bayesian network has been widely applied in different topics from artificial intelligence to risk analyses. Such popularity is due to the representation of the dependability of the elements of an event through the use of conditional probabilities, Weber et al. (2012). This method allows predictive and diagnostic analyses or a combination of both. Also, Bayesian networks accept new information, coming from different sources, that can be used to update the model and to adapt it to the new system conditions, Korb and Nicholson (2004). The credal approach contains all the mentioned advantages plus the implementation of interval probabilities encloses the epistemic uncertainty of missing or defective data.

In this article, it is proposed the use of the credal network approach, as a robust support tool for fire risk assessments. This work attempts to deliver the necessary knowledge to make informed decisions without unreal assumptions and taking into account the uncertainty and complexity of fire accidents. This methodology is applied to the specific case of the Grenfell Tower fire as an effort to incorporate the rigour of a robust mathematical approach to the different qualitative analyses in literature as that produced by Macleod (2018).

2. THEORETICAL FRAMEWORK

2.1. *Fire Risk assessment*

A "fire scenario" refers to a sequential fire event connected by the conditions of success or failure of fire protection measures. The "fire event" is defined as the occurrence of the accident related to the initiation or growth of a fire or smoke spread, or the evacuation of inhabitants or firefighting response, Yung (2008). The number of fire scenarios depends on all the possible permutations that can be built considering the relevant fire protection measures and the fire hazards.

A fire *risk assessment* consists of assigning magnitudes and probability measures to the unwanted fire scenarios and their consequences, Hasofer et al. (2007). The production of a solid fire risk assessment should cover factors like risk to life, property and economic losses, loss of business among others. To calculate such risks the following equation is used;

$$R = \sum_i (P_i \cdot C_i) \tag{1}$$

In the equation 1, the expected risk R is given by the summation of the all probable scenarios. Thus, the expected risk corresponds to the addition of the probability of each of the fire scenarios, P_i, multiplied by the expected number of consequences C_i like number of fatalities, for each scenario, Yung (2008).

The basis of incomplete information must be taken into account through uncertainty quantification which can be divided into two branches. The first is regarded as "knowledge uncertainty" which refers to the lack of information about the factors making up the model, e.g., lack of knowledge about the number of combustible materials in a room when firing ignition. The "stochastic uncertainty" corresponds to the randomness of the events involved in the model, e.g., the fire growth rate in a certain type of building. Such parameters are considered when using credal networks.

2.2. *Credal networks*

A credal network can be regarded as a generalisation of Bayesian networks for imprecise and incomplete probabilities. As in the Bayesian case, a credal network is a probabilistic graphical model to study the systems under uncertainty built from different types of data sources. The outcomes of this technique correspond to the probabilistic distribution of a set of variables when prior information about the system and (or not) new evidence is known, Jensen and Nielsen (2007). The components of the system are modelled by, the probabilistic objects called, random variables. However, probability measurements are not represented by probability mass functions ($P(X)$) but by *credal sets* ($K(X)$), Cozman (2000). In the network graph, the variables are represented by nodes connected by edges denoting their dependencies. A node is a child of a parent node only if there is a direct connection, via an edge, starting on the parent and finishing on the child node, Korb and Nicholson (2004).

Since credal sets are part of the imprecise probability theory, a probability query, different bounds must be computed for the same query variable. The lower probability bound $\underline{P}(x_0)$ of an event x_0, known as the queried variable, is given as,

$$\underline{P}(x_0) = \min_{P(X_i|\pi_i)\in K(X_i|\pi_i)} \sum_{x_1,\ldots,x_n} \prod_{i-0}^{n} P(x_i|\pi_i) \qquad (2)$$

Here, the expression $K(X_i|\pi_i)$ correspond to the credal set of variable X_i given its parents π_i. The upper bound is computed by obtaining the maximum of the expression in Equation 2. The prior probabilities are stored in the *conditional probability tables*. Such prior probabilities must be defined when modelling the system.

2.3. Inference computation

Calculation of a posterior probability distribution of a node of interest (queried node, $P(x_0)$) by using prior probabilities, $P(e|x)P(x)$, and new information about the system called evidence, $P(e)$ (although not necessarily), is known as probabilistic inference or belief updating, Korb and Nicholson (2004).

Inference computation is the warhorse tool to perform analyses with Bayesian networks. The main two analyses are diagnostic and prediction, Jensen and Nielsen (2007). The implementation of exact inference methods, e.g. marginalisation, allows the computation of the exact bounds of the queried variable intervals. Though, such methods are computationally expensive due to the exponential growth of bound combinations, Tolo et al. (2018).

3. METHODOLOGY

Unlike other analyses performed with Bayesian networks available in literature, Matellini (2012), this fire risk assessment prioritises the quantification of the contributions to safety and risk. The posterior probabilities are used to calculate the risk value for each factor. The model was built according to the procedure shown as follows,

- *Definition of variables*. All the factors relevant to the study are defined as well as their dependencies and causalities.
- *Data collection and process*. Sources of information are used to gather information about the variables in the network. Then, data is processed to build the conditional probability tables with probabilistic information of the form: probability of an event given certain conditions.
- *Fire scenario definition*. Different conditions are assumed in order to define the fire scenarios by inserting evidence in the required variables. Specific nodes are queried to study the consequences of such scenarios.
- *Interpretation of data and risk calculation*. The probability values obtained with the inference method are used to compute and analyse the risk of the fire scenarios defined.

4. MODEL

4.1. Variable definition

Calculation of a posterior probability distribution of a node of interest (queried node, $P(x_0)$) by using prior probabilities, $P(e|x)P(x)$, and new information about the system called evidence, $P(e)$ (although not necessarily), is known as probabilistic inference or belief updating, Korb and Nicholson (2004).

The data has been obtained from information stored in tables developed by data annalists, expert judgements, newspaper articles and historical records. During the data collection, it was found that some variables presented different magnitudes for the same event depending on the source consulted. Instead of making assumptions or averaging such values, the model is capable of taking into account the epistemic uncertainty associated to such disagreements and/or lack of data by using probability intervals. Some models present the variables grouped as stages of fire on different times, e.g., Matellini et al. (2018). In this model, the variables are grouped prioritising the contributions to safety and to risk.

4.2. Contributions to Safety

In this model, it is assumed that the smoke detector is contained inside the smoke and fire alarm directly. The *smoke alarms* has a probability of 0.184 of reducing fire damage. Its complement, 0.816 corresponds to the probability of successfully contributing to suppress fire. This condition is represented by its child node *fire fighting*. The contribution of *sprinklers* to the *fire containment* has a probability of 0.912 being one of the most effective systems to suppress fire in buildings, Thomas (2002).

According to Yung (2008) the *regular evacuation drills* node shows there is a probability of 0.80 of performing successfully drills to evacuate people more efficiently during a fire. This node is parent as well as *time of day*, which contains the information of the hours during the day for people to be awake or asleep. The probability of being day hours (from 6:00 am to 12:00 am) was defined as 0.75. Thus, there is a probability of 0.7 having a fast evacuation (less than 4.2 minutes when having a large fire according to Yung and Benichou (2002)) when all conditions are optimal.

In the Table 1002 related to response times in dwelling fires of the fire statistics data tables of the (Home Office UK (2018)), it is shown that the success of firefighters during the 2013-2014 period was of 89.44%.

4.3. Contributions to Risk

According to the Fire Statistics data tables, Home Office UK (2018), the more recurrent causes of fire in dwellings are as those shown in Figure 1 and have been classified in the network as *natural causes*, *deliberate causes* and *installation conditions*.

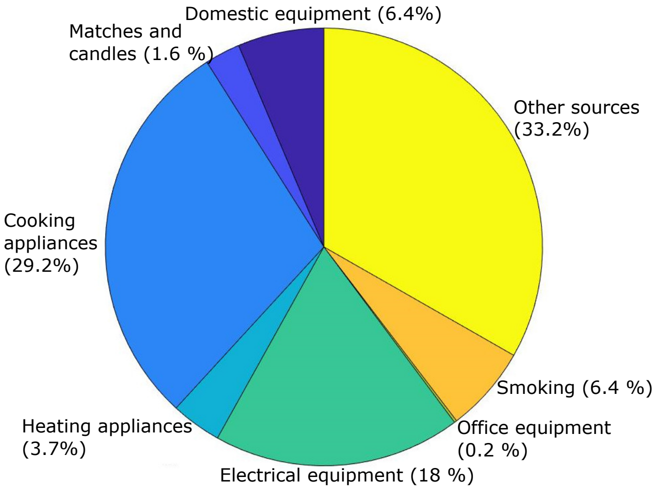

Figure 1: Main sources of fire ignition in England during the 2017/18 period.

Smoking node refers to the case when the inhabitants of the building possess objects that are used to smoke as cigarettes or e-cigarettes. The heuristics process used here is that in 2013, 0.19 of the British population smokes and from those, according to Cancer Research UK (2014)), 0.17 live in a flat, as reported by BBC NEWS (2007). Then, there is 0.0323 probability that the population that live in a flat could have a smoking material. However, there is a probability of 0.05 that smoking activities caused a fire.

In the report about the UK population (M. Randall (2017)), it is found that on 2017 18% of the community were over 65 years. This is expressed as elderly state of the *inhabitants age* node.

The *fatalities* variable represent the probability of a deathly victim, in a purpose-built flat higher than ten stories, once a fire has occurred. From the data recorded in the Fire Statistics tables of the Home Office UK (2018) (Tables 0205a and 0205b of the period from 2009 to 2017), the highest probability of fatality is 0.09 corresponding to the year 2017. The lowest probability corresponds to 0.0025 for 2013. This is shown as a rate of fatalities and the number of fires occurred per year in Figure 2. This is modelled in the *fatalities* interval node of the Bayesian network presented in Figure 3. Table 0801 regarding fire-related fatalities by the hour of the day, it is reported that only 12.8% of the fire events happened during the asleep hours during the same period. However, the slightly more than a quarter (26.8%) of the total fatalities occurred between midnight and 6:00 am.

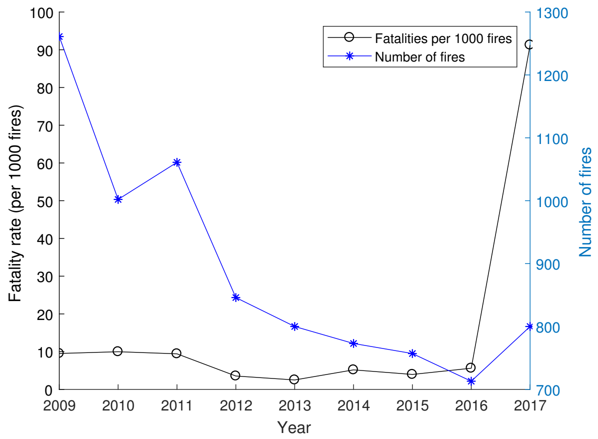

Figure 2: Fire related fatality rate in build-purpose flats in England, left y-axis circles. Number of fires, right y-axis stars. During a period from 2009 to 2017.

Data from an internal report of the National Research Council of Canada (Gaskin and Yung (1993)) was used to obtain the probability of the *fire size* node. The probability intervals are $[0.155, 0.183]$, $[0.600, 0.630]$ and $[0.187, 0.245]$ for flashover, non-flashover and smouldering fires, respectively.

5. Case study: The Grenfell Tower Fire

The unfortunate accident happened on 14 June 2017 at the Grenfell Tower in London had many factors that lead to 72 fatalities and many harmed people. Reports state that the fire was initiated by a fridge-freezer explosion, Macleod (2018), modelled as a possible cause by the node *electrical appliances*. After this tragic event, the fatality rate in purpose-built flats of ten or more storeys increased to 91.2 fatalities per 1000 fires in 2017.

After a building renovation that took place on 2015-16, residents were complaining about the conditions of the fire escape route and safety conditions. It was reported the existence of only one escape route oftentimes blocked by refuse and the absence of fire, smoke alarms and sprinkler system Tucker (2017). During the fire, residents were advised by the emergency services to remain inside their flats. This measurement is called the "stay-put" policy. Such policy, even though it diminishes mobility to evacuate the building, it was recommended to protect inhabitants from the flames and thick smoke accumulated in the lower storeys, Macleod (2018).

The material used in the external cladding of the building was aluminium shaped as panels. Although these panels are cheaper, their core is been proved to be highly flammable being the reason for a fast fire escalation the early morning of the 14^{th} June. For this reason, aluminium cladding has been advised by safety experts to be banned in buildings higher than four storeys in Germany and the USA Macleod (2018).

As the fire incident happened during the asleep night, the ratio of fatalities increased from 26.8%, as explained in the general model section, to 39.3%. This new information is considered as evidence in the *fatalities* node in the network, given the time of the fire event represented by the *time of day* node.

5.1. *Fire Scenarios*

Definition of the fire scenarios is based on the what-if analysis, that can be performed through inference computation in Bayesian networks. Different settings are presented in order to produce a risk assessment with the outcomes of variables that can be relevant for decision makers. It has to be noted that the fire occurrence is always present in all of the scenarios (as the Grenfell Tower fire is being studied) with the purpose of studying how much the probability of a disaster could have been reduced if certain conditions would have been taken.

5.1.1. *Scenario 1. Optimistic analysis*

In this scenario, the general conditions are set as good. This means that all the factors involved in the system are considered as being in working conditions. The purpose of this scenario is to use it as a

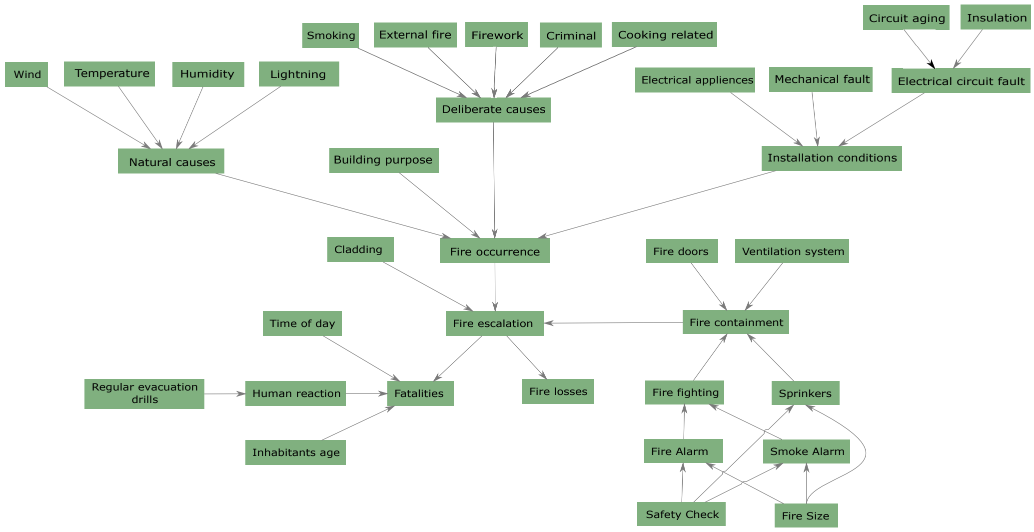

Figure 3: Credal network for fire risk assessment build in OpenCossan, Patelli (2016).

reference to compare it with the rest of the scenarios.

5.1.2. Scenario 2. Grenfell Tower conditions

The state of each of the elements at the moment of fire is modelled in this scenario. As mentioned in section 5, safety conditions at the Tower were precarious. It was reported that fire and smoke alarms, as well as sprinkler system, were not installed.

5.1.3. Scenario 3. Stay-put policy

Scenario 3 is dedicated to the analysis of the "stay-put" policy that was implemented in the building's own safety regulations. Ordering inhabitants to remain inside their flats diminishes the capacity of human reaction. The analysis considers the reaction of victims as "slow" to study the risk of fatalities triggered by the emergency-line instructions given during the fire.

5.1.4. Scenario 4. Fire containment systems

This scenario refers to the fact that safety systems have a big impact on the development of fire escalation phenomenon when having a fire occurrence. The nodes related to fire and smoke alarm, sprinklers and fire fighting conditions are set as fully working to compare with the results obtained in section 5.1.2.

5.1.5. Scenario 5. Cladding influence

One of the most argued causes of fire escalation in the case Grenfell, is the type of material used for cladding. This scenario models the effect of using cladding with a fire-retardant core. By setting up the *cladding* node's state as "non-flammable" the differences in the outcomes can be compared with scenario 2 for analysis.

6. Results and discussions

The probabilities of the queried variables for each of the fire scenarios are shown in Table 1.

6.1. Discussion

6.1.1. Fire Scenarios

In Table 1 can be observed that overall, the probability of having fatalities in optimal conditions, scenario 1, are reduced by two orders of magnitude compared to those in scenario 2.

The "stay-put" policy implemented during the Grenfell fire, was such a crucial factor to reduce the human reaction and increase the number of fatalities. Scenario 3 shows that the interval probability of fatalities could have been decreased about 5.7 to 7%, compared to that in scenario 2, without the "stay-put" policy. Such outcomes verify that the human reaction can be seriously affected by the lack of mobility of the inhabitants during the fire. The fatalities also could have been decreased by implementing more fire evacuation routes.

The simulation carried out for scenario 4 showed on Table 1, demonstrates the influence of having in good conditions containment system, increases the

Table 1: Probability outcomes of queried variables for each fire scenario. The states of each variable are as follows; Fire occurrence=Yes, Fatalities=Yes, Fire escalation=Fast, Fire containment=Successful.

Variables \ Scenarios	1	2	3	4	5
Fire occurrence	[7.41E-3, 9.35E-3]	[1.20E-4, 1.4E-4]	[1.20E-4, 1.4E-4]	[1.20E-4, 1.4E-4]	[1.20E-4, 1.4E-4]
Fatalities	[6.54E-3, 9.12E-3]	[0.115, 0.145]	[0.047, 0.089]	[9.81E-3, 1.15E-2]	[0.041, 0.056]
Fire escalation	[0.115, 0.221]	[0.857, 0.932]	[0.857, 0.932]	[0.447, 0.502]	[0.501, 0.571]
Fire containment	[0.825, 0.989]	[0.189, 0.311]	[0.189, 0.311]	[0.862, 0.968]	[0.189, 0.311]

probability of having a successful fire containment to $[0.862, 0.968]$ compared with that in scenario 2 that is of only $[0.189, 0.311]$. Also, the influence of each of the systems; the fire, smoke alarms, sprinklers and fire doors, was queried to study the most effective component to contain fires. It was found that having sprinkler systems is the most reliable when the fire is large enough to activate the sensors. It is recommended to install such gadgets in buildings since they not only contain the fire but also can mitigate it, Hall (2010). Having the same type of fire doors as the ones in Grenfell, can be considered as a national safety issue that has to be solved.

The successful fire escalation probability, going from $[0.115, 0.221]$ to $[0.501, 0.571]$, in scenario 1 and 5 respectively, means an increase of the flammability of the materials that facilitate fire propagation. This result confirms that the use of flammable materials can cause the fast fire spread occurred at Grenfell.

6.1.2. *Expected risk*

Using Equation 1 the expected risk of fatalities can be computed taking into account the information in the different reports consulted. From Table 1, in the period between years 2009 to 2016, on average there were six fatalities per fire. That value multiplied by the interval probabilities of fire in the conditions of scenario 1 results in a risk interval of $[0.044, 0.0561]$ fatalities per fire. The risk of economic losses is computed by taking the losses per fire which corresponds to £1.66 million per fire. This value multiplied by the same interval probability of fire results in $[£12,328, £15,521]$ per fire.

In scenario 2, the number of fatalities is 72 and the economic losses are £1.5 billion. The expected risk of fatalities results is $[0.0086, 0.01]$ fatalities per fire. The risk of economic losses is given in the interval $[£1.8E5, £2.1E5]$ per fire.

7. CONCLUSIONS

A credal network is presented in this work with the purpose of analysing the effect on the risk of the safety mechanisms once there is the presence of fire. This is, the model allows to study probabilistically the impact of the conditions of a safety mechanism (e.g., fire doors) in the event of a fire. The network also allows to model fires that can be caused by natural causes or deliberate causes like fireworks, criminal behaviour, among others.

The results obtained by means of credal networks, capture the epistemic uncertainty due to the lack of information and differences in the values found in data sources. The posterior probabilities are used to provide approximations to the expected risk of fatalities and economic losses. The model presented aims to be part of a decision support tool for the improvement of fire safety appliances. Further research is being carried out to improve the model structure using learning Bayesian network algorithms.

8. ACKNOWLEDGEMENTS

The first author gratefully acknowledges the *Consejo Nacional de Ciencia y Tecnología (CONACyT)* for the funding that allowed this research project. Special thanks to the former Mechanical Engineering student BSc Mohanad Khalid Al-Shabibi for his contribution to the Bayesian network model presented in this article.

9. REFERENCES

BBC NEWS (2007). “Homes in the UK, <http://news.bbc.co.uk/1/shared/spl/hi/guides /456900/456991/html/nn3page1.stm>.

BBC NEWS (2018). "Grenfell Tower fire: Police ask for £38m to fund investigation, <https://www.bbc.co.uk/news/uk-42569620>.

Cancer Research UK (2014). "Tobacco statistics, <https://www.cancerresearchuk.org/health-professional/cancer-statistics/risk/tobacco#heading-One>.

Cozman, F. G. (2000). "Credal networks." *Artificial Intelligence*, 120(2), 199–233.

Evans, S. (2017). "Grenfell Tower fire insurance loss estimated at up to £1 billion - Reinsurance News, <https://www.reinsurancene.ws/grenfell-tower-fire-insurance-loss-estimated-1-billion/>.

Gaskin, J. and Yung, D. (1993). "Canadian and U.S.A. Fire Statistics for use in the Risk-Cost Assessment Model, Internal Report." *Report No. 637*, Institute for Research in Construction, National Research Council Canada, Ottawa (January).

Hall, J. R. (2010). "U.S. Experience with sprinklers and other automatic fire extinguishing equipment." *Report No. February*, National Fire Protection Association, Quincy, MA.

Hasofer, A. M., Beck, V. R., and Bennetts, I. D. (2007). *Risk Analysis in Building Fire Safety Engineering*. Routledge, Oxford, U.K.

Home Office UK (2018). "Fire statistics data tables - GOV.UK, <https://www.gov.uk/government/statistical-data-sets/fire-statistics-data-tables#fatalities-and-casualties>.

Jensen, F. V. and Nielsen, T. d. (2007). *Bayesian networks and Decision Graphs*. Springer New York, New York, USA, 2nd ed. edition.

Khakzad, N., Khan, F., and Amyotte, P. (2011). "Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches." *Reliability Engineering & System Safety*, 96(8), 925–932.

Korb, K. B. and Nicholson, A. E. (2004). *Bayesian Artificial Intelligence.* Chapman & Hall/CRC, Boca Raton, U.S.A.

M. Randall (2017). "Overview of the UK Population." *Overview of the UK population: July 2017*, (November), 1–17.

Macleod, G. (2018). "The Grenfell Tower atrocity: Exposing urban worlds of inequality, injustice, and an impaired democracy." *City*, 22(4), 460–489.

Matellini, D. B. (2012). "A Risk-Based Fire and Rescue Management System." Ph.D. thesis, Liverpool John Moores University, Liverpool John Moores University.

Matellini, D. B., Wall, A. D., Jenkinson, I. D., Wang, J., and Pritchard, R. (2018). "A Three-Part Bayesian Network for Modeling Dwelling Fires and Their Impact upon People and Property." *Risk Analysis*, 38(10), 2087–2104.

Patelli, E. (2016). *Handbook of Uncertainty Quantification*. Springer International Publishing, Cham, Chapter COSSAN: A Multidisciplinary Software Suite for Uncertainty Quantification and Risk Management, 1–69.

Thomas, R. (2002). "Effectiveness of fire safety components and systems." *Journal of Fire Protection Engineering*, 12, 63–78.

Tolo, S., Patelli, E., and Beer, M. (2018). "An open toolbox for the reduction, inference computation and sensitivity analysis of Credal Networks." *Advances in Engineering Software*, 115, 126–148.

Tucker, P. (2017). "The Grenfell Tower Fire was the End Result of a Disdainful Housing Policy, <https://www.theguardian.com/commentisfree/2017/jun/20/grenfell-fire-housing-policy-social-housing-tenants>.

Weber, P., Medina-Oliva, G., Simon, C., and Iung, B. (2012). "Overview on Bayesian networks applications for dependability, risk analysis and maintenance areas." *Engineering Applications of Artificial Intelligence*, 25(4), 671–682.

Yung, D. (2008). *Principles of Fire Risk Assessment in Buildings*. John Wiley & Sons, Ltd, Toronto, Canada, first edit edition.

Yung, D. T. and Benichou, N. (2002). "How design fires can be used in fire hazard analysis." *Fire Technology*, 38(3), 231–242.