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Risk of human fatality in building fires: A decision tool using Bayesian networks

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ABSTRACT

The Netherlands is the most densely populated country of the European Union, which makes space very expensive. This leads to increasing complexity of the cities' layout and other public spaces, together with a large number of people involved. Authorities would like to know whether new and innovative building designs ensure an appropriate level of safety of people in case of fire, before the accident happens, and to be prepared for the so-called "low probability–high consequences" accidents. Therefore, they need a tool to help them estimate the extent of a fire in a building, given any combination of possible conditions and any unexpected course of events during an emergency. This paper discusses the possibility of using Bayesian belief nets for this task. Using this approach, the people in charge can take decisions at different stages of the design process of a building regarding the location, the structure, the loading of the building, the types of fire protection systems inside the building, as well as the characteristics of the fire brigade that fights the possible fire. In the current study, usefulness of the approach is investigated using a small example. This will show the feasibility of the approach for the Netherlands situation and give authorities involved confidence that building a large comprehensive model would fulfil their needs for a support tool in the planning process. The effort to gather real data therefore was restricted as demonstration of fitness for purpose was the primary objective.

1. Introduction

The complexity of our society is continuously increasing. Advanced technology allows the accommodation of a large population with increasing demands on goods and mobility in the very small space that the Netherlands provide. Therefore, the available space is used at maximum. As an example, preparations are made to build a roof over several kilometres of a 10 lane highway – that carries dangerous goods – and to build offices and may be even houses on top of it. But this intense use of space does not go without a price. There is an increased potential for an accident to become a large-scale disaster. For example, an explosion of a track carrying dangerous goods on the highway mentioned above may end in a large number of causalities among the people living or working in the buildings on top of the highway. Although such an accident remains a rare event, its consequences can reach a large extent. Therefore, the authorities would like to know the consequences of such an accident and to prepare for intervention, before the accident happens.

The people in charge of taking decisions in the design phase of such a complex project need a tool that helps them to choose among the alternative designs that one which ensures with a certain probability the smallest damage. Given the fact that solutions for the large demand on space are innovative designs, the outcome of a possible accident and in particular a fire in such a building cannot be estimated based on past experience and statistical data. Moreover, prescriptive codes cannot be applied to these innovative designs. Therefore, new methods to test the level of safety of people inside buildings are needed. These methods should take into consideration all uncertain conditions in which a future possible fire could take place and, therefore, should be based on computer simulations.

There is a large range of models that simulate the evacuation of a building, from simple models that simulate only the movement of people within the building, to very complex models that attempt to incorporate human behaviour [1,2]. They are used in order to decide on the structure of the building, the position of the exits, the size of the doors, corridors, and staircases. They can estimate the time needed to evacuate the whole building or only some parts of the building. They help also to find bottlenecks of a building regarding evacuation (where people may be trapped, where queues can be formed, etc.). However, they cannot consider the conditions outside buildings, for example, how neighbourhood of buildings, weather conditions, or intervention of fire fighting services can influence evacuation, and, implicitly, the outcome of a fire in terms of number of deaths. As an example,

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one of the tunnels in the High Speed Railway Line is designed for quick evacuation of passengers from the tunnel but further investigations, with the tunnel already finished, show that there is not enough space at ground level to accommodate the fleeing crowd, let alone vehicles and equipment of emergency services. This example shows the need to include in models not only people evacuation, but also fire development and rescue services' actions, taking into account the characteristics of people and structure, location, and the external factors. For this particular case, if all these factors are included into the Bayesian belief net (BBN) model, one may set values for the available safe place and may obtain that the number of people at risk is high, or that the probability to have a high-consequence fire is high.

The goal of the model presented in this paper is to put together not only people and their behaviour during evacuation, but also fire fighters' actions, structure of the building, and characteristics of the building and the environment, in an overall model. Model results are more useful in a comparative sense rather than in an absolute sense. Using this tool, more alternatives can be compared with each other, with the actual level of safety, the desired level of safety, or with existing codes and procedures. The model could be used to analyze the "what-if" scenarios, as well as the low probability–high-consequence scenarios.

The model proposed in this paper is based on the Bayesian belief net approach, a probabilistic method that can accommodate the complexity of the system under analysis. In Section 2 of the paper, the approach chosen to reach the goal of the work is presented. This section is a short summary of general characteristics, advantages and disadvantages of this method, comparisons with methods used before, and a short presentation of attempts to use the BBN approach in the field of fire safety. The model for percentage of deaths in a fire is presented in Section 3. Three phases of building up the BBN model for fire safety are presented here. First, the process of building the graphical structure of the network and of quantifying it is succinctly described. The last part of the section presents some example of analysis and results that can be obtained using this method in order to give an idea about applicability of the BBN approach for the estimation of probability distribution of percentage of deaths in case of fire. The last section of the paper presents the conclusions and gives directions about the future work to be done.

2. Method

In recent years, fire regulations in the Netherlands have tended to change from prescriptive codes to performance-based regulations. This change of principles makes possible more flexible and innovative designs and cost-effective structures. However, it also increases the number of studies that involve risk analysis by demand of authorities, who want to be assured that the solutions chosen are acceptable. This section of the paper presents three methods that are used in risk analysis in general and fire safety in particular.

2.1. Basic principles of fault tree and event tree analysis

Event tree (ET) and fault tree (FT) methods are very popular and diffused techniques for analyzing large critical systems. While the FT method is used to analyze causes of failure of systems, the ET technique shows consequences of such an undesired event. The FT method is a top-down approach, starting with the unwanted event, also called top event, which is the failure of the system, and analyzes different ways in which it can occur. Each event is characterized by the probability of occurrence and non-occurrence, and the probability of the top event can be computed. On the other hand, the ET analysis begins with an initiating event and consequences of that event are followed through a series of potential paths. Each event is assigned a probability of occurrence and the probability of various possible outcomes can be computed. Thus, the ET method is a forward method with an intuitive character; but it does not explicitly represent the state of the system and its environment, which may influence the consequences of the events.

The ET method represents the process as a chronological sequence of events, hence using a linear time order. On the other hand, the FT analysis is not able to capture sequence dependencies in a system. A more complex version of FT, called dynamic FT analysis, can include the sequence dependencies, but it has the disadvantage of being difficult to be implemented [3].

Another major disadvantage of FT is the fact that it can incorporate only binary events (working/not working). This condition is more relaxed in the ET analysis, where discrete events with more than two states can be modelled. But, still, only events with a finite number of states can be modelled. This characteristic of the two methods makes their application in the field of fire safety to be based on many assumptions, which limits the subject of the analysis. For example, there are many events or factors influencing the outcome of a fire in a building that have not only more states, but a continuous set of states. Moreover, they cannot be discretised. An example of such a factor is the time until people start the evacuation in a building. If one wants to discretise this factor as "small", "medium", and "large", the question is what would be the interval of values for each of the categories. The best way to model this factor is to assume that it is a continuous random variable following a certain distribution.

Moreover, in the FT analysis, relations between events and causes are represented by means of logical AND/OR gates. In the process of a fire in a building, there are many uncertainties and, usually, the occurrence of a combination of certain events does not ensure the occurrence of another event, but rather does influence the probability of occurrence of that event. For example, poor training of occupants of a building and a late alarm time make a longer evacuation time more probable. It is not for sure that the evacuation time is longer, because there may be some other factors, such as a small distance to exits, which may reduce the evacuation time.

The big disadvantage of both FT and ET methods is that they are not able to capture the dependability between events. This is a main characteristic of a fire in a building, in which there are multiple dependencies between factors. For example, area of the building influences both the time until critical conditions are reached and the evacuation time. Hence, random variables associated with the time until critical conditions are reached and the variable associated with the evacuation time are not independent variables.

FT and ET analyses have been applied successfully in many fields, and also in the field of fire safety [4]. In [5,6], the ET approach was used in order to compute the risk to which occupants of a building may be subjected if a fire breaks out in that building. The branches of the ET used in these papers denote the functioning/failure of the protection systems (alarm, sprinklers, and emergency doors). Using the ET approach, scenarios were defined and for each of the scenarios, the probability of occurrence and the consequences were computed. In [7], the ET approach was used in order to quantify the risk in chemical process industries. However, in all these references, only parts of the complex system of a fire, for example fire suppression systems, are considered. None of these papers includes all the parts involved in a fire in a building (such as fire, building itself, people inside the building, fire brigade, and environmental conditions). Moreover, the variables included are characterized by two states, functional/non-functional.