SAFETY SCIENCE Monitor

Issue 2 2007

Article 4

VOL 11

# MODELLING SELF-RELIANCE, EVACUATION AND FIRE FIGHTING ACTIVITIES DURING A LARGE FIRE IN A PUBLIC BUILDING – A DYNAMIC APPROACH

D.M. HANEA, H.M. JAGTMAN, S. SILLEM & J.W.F. WIERSMA
Safety Science Group, Delft University of Technology

Corresponding author: Safety Science Group, Faculty of Technology Policy and Management, Delft University of Technology. PO Box 5015, 2600 GA DELFT, The Netherlands. D.M.Hanea@tudelft.nl

Abstract: This paper presents a dynamic model that describes the processes that take place in a fire in a public building combining accident process models with system models. The model links the development of a large fire in a public building with the activities of fire fighters and with the evacuation of people.

The model helps in finding an order in the occurrence of events during a fire in a public building taking into account all three processes (fire development, people evacuation and fire fighting actions) and especially the interactions between them. The three processes are analysed separately and then combined into an integrated dynamic model. There are two main sources of uncertainty regarding the order of events that occur during a building fire in which evacuation is needed: the way in which the fire brigade is notified about the existence of the fire and the moment when the fire fighters are ready to start the intervention at the place of the accident, compared with the stages of the evacuation. Four cases result from these uncertainties. These uncertainties, resulting in the four cases, introduce the dynamics in the model.

The resulting model is used in two disaster management related studies. The first project aims at supporting decision making during the design phase of large public buildings, the second project focuses on alarming the population in an evacuation situation. The paper shows preliminary results to indicate how the dynamic model contributes to the studies. Finally some other potential applications of the model are discussed.

Keywords: Disaster prevention, management & control

## INTRODUCTION

Large fires in public buildings are rare events and their occurrence is hard to predict (Lin, 2005). Fires start as complex situations, in which a lot of processes take place. Fire fighting is a task oriented process that aims at controlling and extinguishing the fire. Getting people out of the building is another process that takes place. This is a partially spontaneous process, in which individuals themselves cope with the emergency (self-reliance), and partially an organised process that aims at getting people out of the burning building into safety (evacuation).

Due to their inherent characteristics, it is difficult to describe fires and all the activities that take place around them with a fixed process model. A fire has an uncertain progress. Fire fighting and evacuation activities are adjusted to the development of the fire. The extinction strategy and resources deployed depend on the fire characteristics and progress (Davis, 2001). In a public building, the organisation of an evacuation is a responsibility shared by the company occupying the building and the local fire brigade (Bradburn, 2004). Moreover, the activities necessary to get people out of the building and the fire fighting activities are partly independent processes. For example, the fire brigade may arrive prior to the evacuation, but also while the evacuation is already ongoing or even after it is finished. The nature and function of a building may also be of influence. A study of Proulx and Pineau (Proulx & Pineau, 1996) has shown differences in evacuation behaviour of people in office buildings or apartment buildings.

At present, the relationships between the different processes that take place in a fire in a public building are not well understood. These processes are not described in one comprehensive model that explains their relation. Such a model can help improve the understanding of the link between the processes that take place during an (organised) evacuation in a fire and the fire fighting situation. This paper describes the development of a model that describes the processes that take place using a dynamic systems view. The model links three processes: *the fire itself*, the tasks of the *fire fighting organisation*, and *the evacuation*. The last is partially a spontaneous activity initiated by the people inside the building themselves, and partially an organised activity of rescue services. The model contributes to two PhD projects carried out at the Safety Science Group. The first project aims at supporting decision making during the design phase of large public buildings through the identification of important factors influencing the outcome of fires (Hanea, 2005). These factors involve aspects ranging from structural elements of the building and local infrastructure, to strategies of fire fighting services. The model described in this paper will form the basis of a Bayesian Belief Net used in this project (Hanea & Ale, 2005). The second project focuses on alarming the population in an evacuation situation (Sillem et al., 2005b). In this project the model will form the basis on top of which experimental research is carried out (Sillem et al., 2006).

The basic structure of the model is derived from the systems view on safety used in the Safety Science Group at Delft University of Technology (Hale & de Kroes, 1997). A general framework is presented in the second chapter. The third chapter describes the results of a literature review that is used to define the components for each of the three separate processes. Interviews and educational materials, used to train fire fighting officers, are analysed to identify the possible links between the components of the separate processes. The information gained through literature and interviews is structured into a model, which is presented in the fourth chapter. The fifth chapter describes how the model is used to help define research issues in the mentioned PhD projects.

## GENERAL FRAMEWORK

For our modeling needs the systems view on safety implies two important aspects: the concept of processes from which the normal operation systems can transfer into accidents and the various organisation levels within a system which may provide control measures to counteract the occurrence of an accident.

Accidents cannot be described with a fixed predictable set of well known events. One cannot control an accident similar to how operational processes within systems are controlled. The latter are intended operations which are known in advance. The whole operation of a system is aimed at optimising these kinds of processes. Accidents on the contrary are the results of various processes within a system that were not meant to occur in the first place. We refer to this as deviations from the intended operations. Deviations take the system outside the defined and designed envelope or processes. The full range of deviations in a complex situation as a result, can never be fully known.

The processes which may lead to accidents are the subject of various system process models (e.g., Hale & Glendon, 1987; Kjellén & Larsson, 1981; MacDonald, 1972). These models specify a number of phases into which a system can get. The first phase is the normal operating situation in which hazards are built-in and controlled within certain system boundaries chosen during design of the system. Dynamic systems are constantly changing and may at some point get into stages outside the defined normal process, in other words remaining a deviation from the normal operating process of the system. The phases of the deviation model describe the start of this deviation process and sequentially the stages into which such deviations may get. Not all deviations necessarily result in accidents. Nevertheless, in a stage that is characterised as a deviation from the normal operating process the level of risk is increased. People or measures that are capable to recognise this increased level of risk can intervene and try to get the system back into its normal operation (Hale & Glendon, 1987). If the increased level of risk is not recognised or the actions were not fully appropriate, the system is confronted with a loss of control and the deviation continues into the accident process. At this point the transfer of energy from the hazards to (some of) the targets can no longer be stopped and an accident becomes inevitable. Still, the damage process can be influenced to reduce harm to the targets, both during the transmission of energy and in the stabilisation phase after the accident has happened.

The model necessary to frame fire and evacuation in case of fires, especially includes all phases starting from the moment of loss of control. All relevant measures before hand might have come into action but have not been effective to get the system entirely back into its normal operations. Important for our model is to recognise that a system has deviated from its normal operation and has developed into a stage where loss of control and an accident became inevitable. We focus on all phases after the accident has taken place in which countermeasures can influence the outcome of the accident, in this paper a fire. The accident process models show that no fixed order of events can be predicted. However, a number of sequentially occurring phases may be distinguished. Whether a phase really occurs as well as the damage that results from it, depends on the potential effectiveness of countermeasures. Since we are interested in the interrelations between the fire progress, fire fighting actions and evacuation we only consider these cases in which evacuation is required.

For the types of countermeasures available, the system view on safety defines various organisational levels. A useful structure in this perspective has been introduced by Rasmussen (1997) in his article on risk modeling in a dynamic society. Rasmussen introduces 6 levels running from the “work”, the “staff”, the “management” up to the “government”. Each organisational level has its own potential countermeasures. Since we focus on the accident phases after a loss of control has occurred, measures mainly considered here are aiming at controlling an actual fire, rescuing people and saving properties. Such countermeasures should already be available either in the process (the work in Rasmussen’s terms) itself or must be quickly accessible for individuals at danger and the (rescue) organisation. Mainly the bottom part of the social-technical system introduced by Rasmussen has opportunities to provide such measures. In terms of fire and relating evacuation activities the main organisation levels and related processes can be defined as:

- The fire process taking place (the operational or work level)
- The evacuation of individuals in a building on fire (both individual control and organised evacuation)
- The external fire fighting organisation (organises the control of both the fire process and evacuation of individuals from a building)

Each level has its own related countermeasures to influence the outcome of a fire. In the following section we will first describe what is currently known about the processes at each of these three organisational levels. In the section after that this knowledge is brought together and inter linkages are shown between the different levels.

## CURRENT KNOWLEDGE ABOUT FIRE PROGRESS AND EVACUATION PROCESSES AND FIGHTING ORGANISATION

### Fire process

At the operation level we are interested in regaining control after the moment of loss of control and potential emerging accident processes resulting from a fire. The main process to understand therefore is the growth of a fire in time. The physics of a fire process can be simplified by using the relations between three components: fuel, heat and oxygen. The comparison with a triangle (Chitty & Fraser-Mitchell, 2003) (see Figure 1) is almost obvious: as the triangle needs three sides in order to be sustained, the fire needs all three components in order to burn. Taking away any of the three components removes the right of existence of the fire. Removing any of the tree components or separation these are in fact the basic principles for any fire fighting tactics.

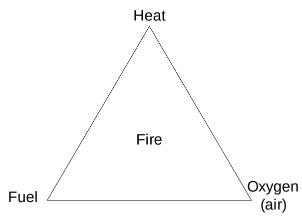


Figure 1: Fire triangle

The usual development of a compartment fire can best be characterised by the temperature-time curve from Figure 2. Three different stages can be distinguished, namely the *growth phase*, the *steady state* in which a fire is fully developed and the *decay phase*. The transition from the growth phase to a fully developed fire is known as *flash over*.

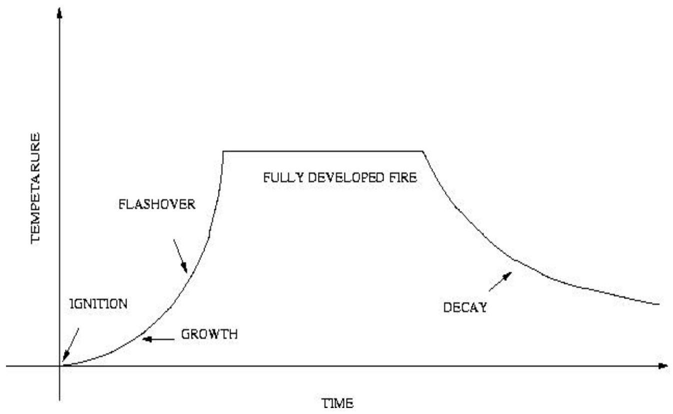


Figure 2: The stages of a compartment fire

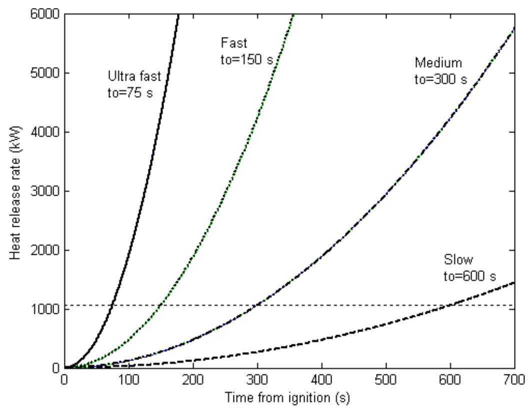


Figure 3: Heat release rate vs. time for different design fires

The most important factor that describes 'how big the fire is' during the *growth phase* is the heat release rate (HRR) (Babrauskas & Peacock, 1992). The HRR characterises best the pre-flashover stage of a fire and is measured in kilowatts (kW) or megawatts (MW). It controls the main characteristics of a fire: the hot gas temperatures and flame heights. The early stage of a fire, growth phase, in which the fuel and the oxygen are virtually unlimited, is characterised by an exponential increasing in the heat release or t-squared curve (Ramachandran, 1985) as in Figure 3. Based on the interval of time after ignition when the HRR reaches a certain value (usually equal to 1055kW), the fires can be classified in slow, medium, fast and ultra fast.

Transition from the growth phase to a fully developed fire (steady state) is very fast and is called 'flashover'. Many definitions of flashover have appeared in literature (Drysdale, 1985), but the most accepted is the following definition: 'the stage of a fire at which all surfaces and objects within a space are heated at their ignition temperature and flames break out at once over the surface of all objects in the space' (Association).

The period of *steady state* in which a fire is fully developed is characterised by a relatively constant heat release rate (HRR). As a result of decreasing concentration of oxygen and/or quantity of fuel, the steady state shifts into the final phase called the *decay period*. This phase is characterised by a continuous decrease in the heat release rate, until the fire is extinguished due to lack of fuel and/or oxygen.

There are multiple computer models that can simulate the development of a fire in a building, together with the fire products (smoke, toxic gases, heat, etc.). At the request of the Forum for International Cooperation on Fire Research, a completely accessible free database[1] of computer models for fire and smoke was made in 1992 (Friedman, 1992). In 2003, a survey made by (Olenick & Carpenter, 2003) identified 186 simulation models from ten countries. Currently, many of these models are improved and there are many others under development. The simulation models mainly aim at obtaining a time-temperature curve as in Figure 2, but they fail to include the influences of fire fighting actions on the fire development.

### Evacuation of individuals: self-reliance and rescue by fire services

In each building that catches fire, people that need to be evacuated may still be inside. From an organisational point of view two relevant types of evacuation can be distinguished: *emergency self-reliance* and *rescue*. The first type of evacuation is related to the level of individuals and rescues services present in a building at the start of the emergency. The second type, *rescue*, is linked to the organisation level headed by the fire services. Rescue is only relevant if there are still people in the building when the fire services arrive at the scene. Self-reliance is related to individuals and is defined as: reliance on one's own efforts and abilities (Bandura, 1986). '*Emergency self-reliance*' in specific is defined as the reliance of building or area occupants on their own efforts and abilities in an emergency evacuation; for this study we further specify this as the behaviour that people present in a building or area show which is aimed at bringing themselves to a safe place from the start of the emergency situation until the moment the fire fighting services arrive. Only means and people present at the scene at the time of the start of the emergency situation can be used. This includes rescue services that are in the building at the start of the emergency. When the fire and rescue services from outside the building have arrived and have taken over the evacuation, this is no longer called emergency self-reliance.

---

[1] see www.firemodelsurvey.com

A literature study (Sillem et al., 2005b) has been carried out to distinguish different phases during an evacuation of a building and to determine how human behaviour in these phases can be influenced. This section only discusses self-reliance and not rescue, as rescue is seen as part of the fire brigades activities and not as an activity carried out by the building or area occupants. This section shows the results of the literature study and describes how these results are used to construct the model that is shown in Figure 4. First the importance of self-reliance in evacuation is explained. After that, the problems with human behaviour and the possibilities for influencing the human behaviour in the phases that were found will be discussed.

### *The role of emergency self-reliance*

To a large extent, the effectiveness of an evacuation depends on the emergency self-reliance of the building occupants. Within the first minutes, a fire may quickly become life-threatening for the occupants when remaining in the building. It is therefore of great importance that the people in a building are self-reliant and are capable to rescue themselves as much as possible in the time from the start of the emergency situation until the moment the fire services arrive. This emergency self-reliance can be influenced in a number of the following phases that occur during an evacuation: detect and alarm by a system or by a person; organised alarm; recognition; response; start of evacuation and end of evacuation.

### *Detect (and alarm) by a system or by a person*

When there is a fire in a building it takes some time for the rescue services in a building to notice the fire and to warn the fire services. Before the organised alarm can start, the fire has to be detected by a person or by a system. This can be an indirect contribution to self-reliance. Detection is needed to start self-reliance, but alarm is not. The person that detects the fire can immediately take the appropriate action. But for the rest of the occupants to be self-reliant, alarming them is necessary.

### *Organised alarm*

When the fire is detected by a person or by a system, it takes some time for the rescue services in the building to make the decision to start an evacuation. Often, this decision is delayed because of the untrue expectation that people will panic when they find out that there is a fire in the building (Keating, 1982; Proulx & Sime, 1991; Quarantelli, 2002; Sime, 1990). It is better to give people as much relevant information as possible, because people are capable of making the right decision to start evacuating when they are provided with enough information about what is going on. Being told the truth about what is going on is likely to trigger an appropriate response and not dysfunctional behaviour or panic (Proulx, 2000). This does not mean that self-reliance doesn't start until after the start of the organised alarm. Before the organised alarm is set up, a number of occupants may already be aware of the emergency. These people can show self-reliant behaviour before the start of the organised alarm.

Improving the emergency self-reliance of people can be done by giving instructions and warnings during an emergency. These instructions can be present in the building as flight plans, signs and emergency lighting. There are also possibilities for using the building management to give extra instructions during the emergency situation, like intercom messages, or mobile phone text messages. Intercom messages can be pre-recorded or 'live'. The advantage of live message is that new instructions can be given as the emergency situation develops. Moreover, the tone of the voice message can convey its urgency (Proulx, 2000).

When the occupants are being ordered to start evacuating, this is usually done by sounding an alarm bell. Unfortunately, occupants often tend to continue their activities and ignore the alarm signal (Benthorn & Frantzich, 1996). This shows the need for a message clarifying what action should be taken. People may also be so concentrated on their activities that they do not pay any attention to the fire warning system. This implies the need for people's attention to be drawn away from their activities and to the fire warning system, by 'stopping the show,' providing a sudden change in the environment (Proulx, 2000), such as automatically turning off all computers or sending out an intercom message.

### *Recognition of an emergency by occupants*

A model by Bellamy and Geyer (1990) shows the stages of pre-movement time: perceiving the warning correctly, making a correct decision about what is going on and then showing the right response to the situation. The problems and possibilities for influencing human behaviour in these phases are discussed here. When people notice the fire warning, they have to interpret it as being a credible warning of a real fire situation. People have to understand that immediate action is expected from them. Bellamy (1990) found that people try to gain enough information to confirm the existence of a fire threat. Even direct evidence of a fire (such as smoke) may be insufficient to motivate evacuation due to inaccurate perceptions of the rate of fire growth (Canter et al., 1988). The perceived authority of the warning is an important factor for motivating a response. It also helps for fast evacuation.

After people have interpreted the warning in the right way, they have to judge the situation and make a decision if it is necessary for them to evacuate or not. To improve people's emergency self-reliance, they have to be motivated to get out of the dangerous situation by evacuating the building or area as quickly as possible when ordered to do so, even when they are not trained or familiar with the building at hand.

### *Response, the start of the evacuation*

After people have made the decision to start evacuating, the direction and the exit needs to be chosen. People often choose what they know before the unknown, so they are more likely to use an exit they are familiar with (Benthorn & Frantzich, 1996). This usually is the main entrance / exit. Knowledge of and familiarity with routes are important if they are to be used. This is more important than exit width or the length of the routes. Informative evacuation alarm systems (which provide information instead of just a tone) can be used to give information about the routes that should be used and thus reduce the time spent in the behaviour phase of the evacuation process.

### *People rescued by fire fighters and the end of the evacuation*

At this point, the fire fighters come into the building and start rescuing the people that did not yet get out of the building. People can still rescue themselves at this point, but when people are rescued by the fire fighters, this is no longer called emergency self-reliance, as help from outside is being used. The need for this phase can be influenced by the phases before. When people were motivated to evacuate before the fire fighters arrive, there will be less people left in the building for them to rescue. The arrival of the fire fighters is also the end of the organised evacuation, as they take over the evacuation.

### *How to translate this into a model*

The literature review shows that relevant information is needed to convince people that there is a real emergency situation and that they need to start evacuating immediately. People need to know what is going on, where the danger is located and what they should do to bring themselves to a safe place.

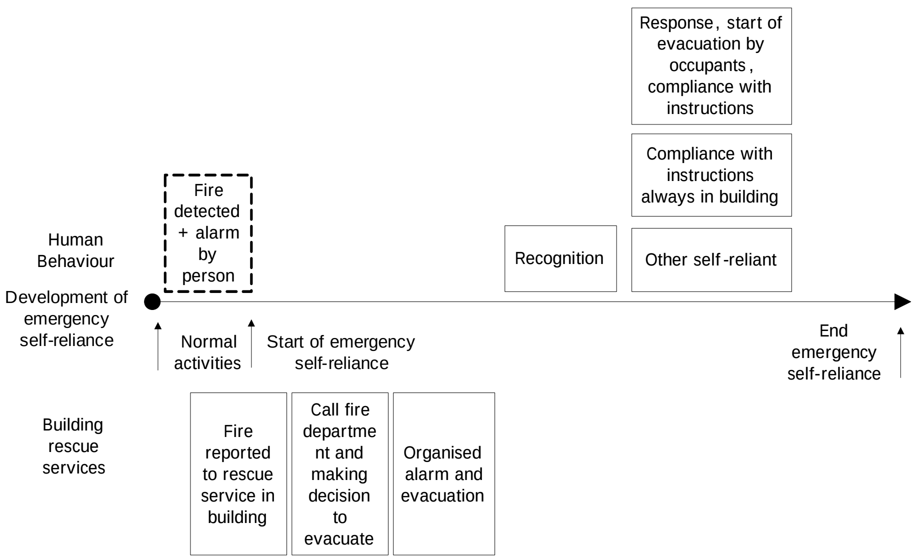


Figure 4: Model timeline course of fire and human behaviour related to emergency self-reliance

A model constructed to show the development of the human behaviour and self-reliance during a fire in a building is presented in Figure 4. This figure shows the phases that have been discussed in this section. It shows the emergency self-reliant behaviour of the building occupants, including the behaviour of the rescue services that are present in the building at the start of the emergency. The rectangles in the upper part of the figure show the human behaviour that changes over time. First, the building occupants show their normal activities. Then, at a certain point they will recognise that something is going on. The time before people start acting is called the pre-movement time. As soon as people start acting, this is the movement time. This pre-movement ends at a different time for each individual, as the time at which people start acting differs from each other. The number of people that show self-reliant behaviour increases over time from the start of the emergency. This means that the people change their behaviour from normal activities to self-reliant behaviour. At the end of the emergency, when the evacuation is ended, the number of people that show self-reliant behaviour decreases again, they change back to normal activities. The same is valid for the response and the compliant behaviour. The 'normal activities' of the occupants decrease rather than increase during the course of the emergency, and start to increase again at the end of the emergency. The 'fire detected + alarm by person' square is surrounded by a dotted line because this doesn't necessarily happen during an emergency. This model can be used to determine at what moments human behaviour can be influenced. It shows in what order events take place and the behaviour people may show. For example, compliance with instructions that are always in the building can start at the moment of the start of the fire, and in time, more and more people will comply with these instructions.

### The Fire brigade organisation

The fire services have two main tasks in intervention in a building fire: *rescue the people inside* the building and *control/stop the fire*. The two tasks can be performed simultaneously (if there are still people inside the building at the moment the fire fighters arrive at the scene of the fire), or only the task to control the fire can be performed (if the evacuation of people has finished before the arrival of the fire fighters). If the fire fighters help the people still inside the building, the self-reliance of those people ends. However, there may be still people inside the building who go to a safe place by themselves, so these people are still self-reliant.

The decisions of a fire brigade from the moment when the fire is notified are based mainly on codes and experience. It is stated in codes how many fire trucks have to be send in case of a fire, depending on the way in which the fire is notified. In the case of Delft Fire Department, if the notification comes from the 112 room (which means that somebody called the 112 emergency room) two fire trucks are sent to the fire scene. If the notification comes from an automatic system only one fire truck is sent, due to the large number of false alarms (CBS, 2004). However, if one additional call at the emergency room is received one more cars can be sent. Based on the number of fire trucks used, the fires can be dividend in small fire (one fire truck) and large fires (two fire trucks). The number of fire trucks used is also related to the number of tasks that have to be performed. Each fire truck is appointed to one task at the time. For example in case of evacuation, one fire truck is appointed to help people to evacuate while another truck has to control the fire. After the evacuation ends, both fire trucks can start to attack the fire and to put it out.

The time line of the fire brigade organisation from the moment when the notification is received until the moment when the fire trucks leave the scene of the accident can be divided in more subintervals[2] as shown in Figure 5. The *dispatch time* is the amount of time needed to process the emergency call, interpret data, select and dispatch units. Then, there is a time interval in which crew receives information and prepares to leave the station, called *preparation time*, turn out time or get out time. The *travel time* is the time period between leaving the fire station of the first fire unit and arriving at the fire scene. The *set-up time* is the time from the arriving at the scene of the incident just prior to the commencement of applying extinguish agent on the fire, in which actions as crew deployment, apparatus placement and apparatus set-up takes place. The next interval, called *fire fighting time*, is the time interval in which the fire fighters attack the fire directly. Depending on the moment when fire fighters arrive at the place of the accident comparing with the stage of the evacuation, the fire fighting interval may have a subinterval (*rescue people time*) in which fire fighters take over the coordination of evacuation from building and help the people who are still inside to evacuate as quickly as possible. Therefore, we will call this interval the *intervention time* and the sum of the time intervals before this moment will be called *time required before intervention*.

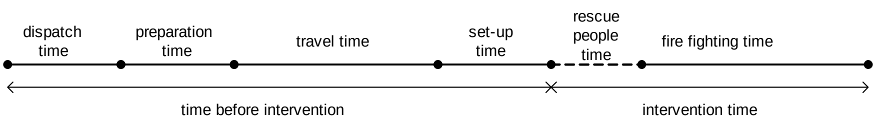


Figure 5: Time intervals of the fire brigade actions

There are too many variables in order to correctly estimate each of the time intervals described above for each fire incident. However, there are some statistics about length of the intervention time interval (CBS, 2004). According to these statistics, 7.9% of the intervention times are less then 5 minutes, 27.3% are between 5 and 7

[2] see http://www.ofm.gov.on.ca/english/FireProtection/model/

minutes, 22.6% are between 7 and 9 minutes, 33.1% are between 9 and 15 minutes and 9.2% are longer then 15 minutes.

As Figure 5 already shows the tasks for the fire services depend upon the situation at the moment the fire fighters arrive. Evacuation is only relevant if people are still in the building at the moment they arrive. Similar the influence of fire fighting activations on the fire growth (see Figure 6) depend on the stage to which the fire has developed before arrival. If the intervention of the fire brigade starts before the flashover has occurred, the maximum temperature reached is lower and the time until the fire is stopped is shorter than in case that no fire fighting activity is performed. If the intervention starts after the fire has fully developed the maximum temperature has already been reached and is not affected. However, the time until the fire stops can be shorter than in case no fire fighting activity is performed. Although the moment of arrival in relation to the state of the fire varies, interventions during multiple stages have effect on the outcome of a fire.

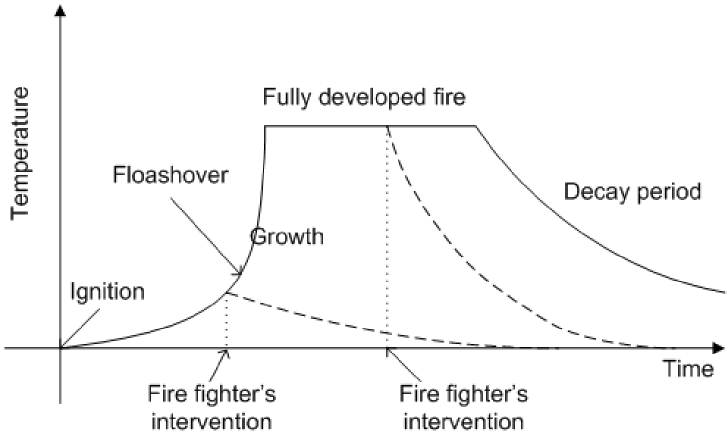


Figure 6: Influence of fire fighting actions on the development of the fire

Therefore, any reduction of the time required by the activities of the fire fighters before the intervention is important and may have a large influence on the outcome of the fire. One possibility to reduce the time before intervention is the way in which the fire fighters receive information about the building and the fire inside the building. They can get this information before leaving the station or on the way to the fire scene, or at the moment when they arrive at the fire scene.

## MODEL

The previous section presents separately the three processes of a fire in a building, with their important moments (see Figure 2, Figure 4 and Figure 5). However, these three processes are not independent and the interactions between them should be explained in order to have a complete picture of a fire situation in a building. I fact, these three processes represent the coordinates that describe in a dynamic way the state of the whole system. The dynamic aspects comes from the fact that the state of each of the three processes at one moment k+1 depend on the state of the processes at the previous moment k. In a formalised way, if the fire stage, the people evacuation and the fire rescue services' actions at moment k are denoted by F(k), E(k) and R(k) respectively, then the whole system is characterised by the following system of equations:

$$\begin{cases} F(k+1) = f_1\big(F(k), E(k), R(k)\big) \\ E(k+1) = f_2\big(F(k), E(k), R(k)\big) \\ R(k+1) = f_3\big(F(k), E(k), R(k)\big) \end{cases} \tag{1}$$

where $f_1$, $f_2$, and $f_3$ are functions expressing the relations between the three processes from one moment to the next one.

There is more or less information about each of the three processes separately (as one can see in the previous section), but there is an acute need for information about the interaction between them, or, in other words about the functions $f_1$, $f_2$ and $f_3$. These interrelations are the basics for the construction of the network used in the BBN approach (Hanea & Ale, 2005).

The course of events for the three processes can be represented by three time lines one for each of the three processes (see Figure 7). Each time line is built up separately using the models presented in the previous section. However, attention is paid to the interactions between the three time lines. Therefore, some of the events presented in the previous section will not appear in the model from Figure 7.

## The three processes in the dynamic model

In the attempt to put together the three time lines, difficulties were found when the *fire process line*, showing the development of a fire, was considered. Fire development can be described separately as in Figure 2, but the numerous factors that have influence on the development of fire can not be put in a chronological order. Moreover, fire is an undesired and unintended process, hence not goal oriented. Therefore, in order to reduce damage, there is need to understand the phases of the fire process and to realise the importance of the intervention by the fire brigade and the evacuation of people as soon as possible. The clear description of the influence of fire fighters' actions and people' evacuation actions on the course of the fire process has too many uncertainties and can not be described in a series of events. Hence, in the model from Figure 7, the fire is represented by the start (the ignition) and the end of the fire, but one has to be aware of the fire development and of the need to evacuate the building and to start to fight the fire as soon as possible.

The activities of individual people inside the building (including the rescue services present in building), *the evacuation process*, are represented in the second line in Figure 7. The key-moments shown in the model first relate to the detection of a fire by a person or by an automatic system. Secondly, these moments are related to emergency self-reliance and rescue by fire fighters (after arrival). One way to reduce the evacuation time or at least the start of evacuation is to help people to interpret correctly the warnings and to take quickly the correct decision, by providing them with relevant information.

In order to include the *fire brigade actions* from Figure 5 into the dynamic model the time intervals before the intervention are not discussed. These are activities that are independent of the development of fire and on the course of the people evacuation. Only the moments when there is a direct interaction between the three time lines are presented in Figure 7. However, it is important to keep in mind that in order to have the intervention of the fire brigade as early as possible in the course of the events, reduction of any of the time intervals is needed. From the time intervals of the fire brigade intervention (Figure 5), only the moment of notification of the fire brigade and the start of intervention are included into the dynamic model.

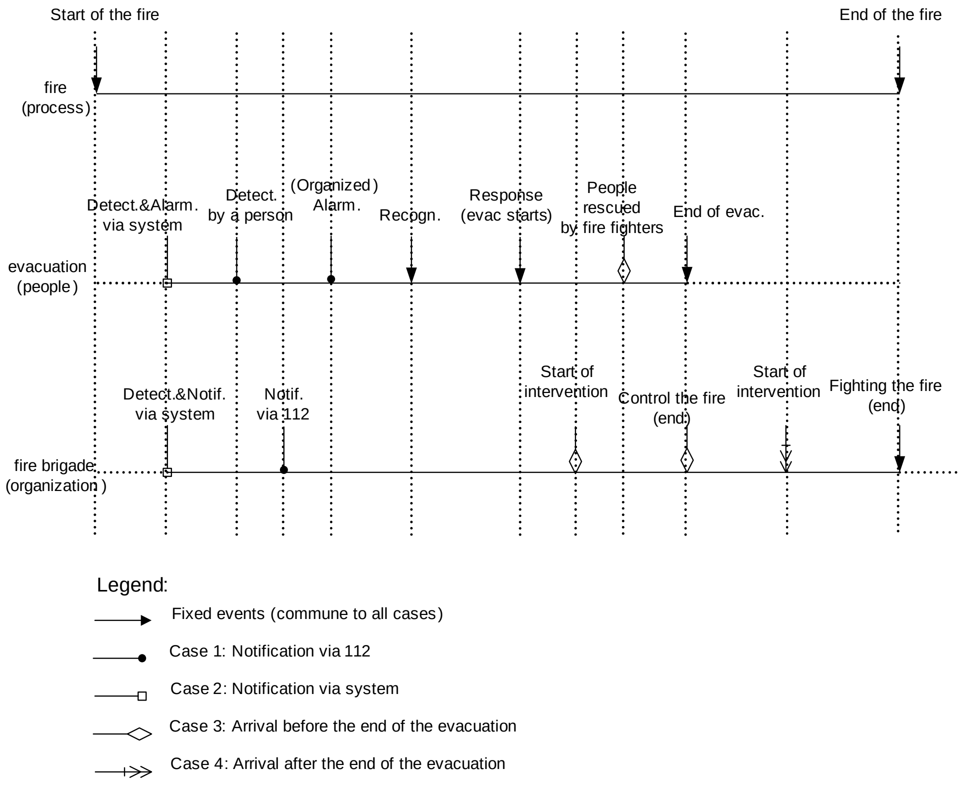


Figure 7: The time lines of the process during a large fire in a public building

### Interrelation between the processes

Since any emergency situation is only partially predictable, the relations between the three time lines cannot be fixed in one sequential order. As stated in discussions with employees from Delft Fire Department, the course of events during a fire intervention varies per event as a result of two sources of uncertainty. These are:

- the way in which the fire brigade is *notified* about the existence of the fire (via 112 or via automatic system);
- the moment when the fire fighters are ready to start the intervention at the place of the accident, comparing with the *state of the evacuation* (the intervention starts during evacuation, or after the evacuation ends).

Based on this conclusion, there are four cases that can be distinguished from Figure 7:

- Case 1: fire notification to fire brigade via emergency room (or 112 room).
- Case 2: fire notification to fire brigade via automatic system existing inside building.
- Case 3: start of intervention before the evacuation of people from building ends.
- Case 4: start of intervention after evacuation ends.

Taking into account above cases, a dynamic view of the relations between the three important time lines involved in a fire in a public building can be obtained. Apart from the three time lines (one for fire, one for people inside the building and the other one for rescue services, or fire fighters) Figure 7 shows the important moments, for all cases indicated above. For each case another symbol is used. The fixed events are those for which the order of apparition is known. They are common for all scenarios. For example, recognition, defined as the moment when people realise the need for evacuation, appears for sure after the alarm sounds and before people effectively start to evacuate. The difference between cases comes from the two sources of uncertainty, namely: the different way in which the fire brigade is notified about the existence of the fire (via automatic system or after a person sees the fire and calls 112) and the moment when the fire brigade starts the intervention at the place of the accident (during evacuation of the people from building or after the evacuation ends).

It has to be mentioned that the length of each interval in the above figure is not important. The length of each interval is also uncertain and depends on many factors. Finding these factors is the subject of future work.

### Explanation of dynamic relations

Cases 1 and 2 relate to the first source of uncertainty: the way the fire brigade is notified. It has to be mentioned that the order of the notification via automatic system and via 112 from Figure 7 can be interchanged. In case that a person sees the fire before the fire alarm starts the notification via 112 may be more quickly. This could for example be the case if no fire alarm is installed, the alarm does not work properly or there is a person but no detector present in the room where the fire starts. However, if the existing fire detectors work properly, they are sensitive enough to detect the fire before any person can notice it. In this case, the notification via the automatic system may be much more quickly. The order chosen in Figure 7 for the two types of notification is not relevant and it can be changed.

- Case 1: When the call to the fire brigade is made via 112 (Figure 7, case 1), it is supposed that a person who observed the fire called the central dispatcher immediately, or after he/she tried to extinguish the fire. The central dispatcher calls than the fire brigade responsible to extinguish the fire at that location. In the mean time, the rescue services in the building start the sound alarm in order to announce the people about the existence of the fire and to start the (organised) evacuation. Only the people in the relevant parts of the building (those that are affected by fire) are warned. The sound alarm should increase the self-reliance of individuals present in the building.
- Case 2: In case that the call to the fire brigade is made via the automatic system exiting in the most public buildings (Figure 7, case 2), there is a delay of three minutes until the sound alarm starts inside the building. However, this delay is almost insignificant from the point of view of the order of events after this moment. So, it can be considered that the fire brigade and the people present in the building are notified in the same time about the existence of the fire.

One more remark for case 1 (notification via 112 by a person in the building), namely the order of notification of the fire brigade through 112 and the start of the (organised) alarming of people in the affected parts of the building can be interchanged. The order of these two events depends on the management of the building, on the training and the role of the person who noticed the fire and on the behaviour of this person. He/she may first call 112 or may announce the reception desk or one of the staff people (in case of a public building). After notifying the fire services the rescue services present in the building may search for more information about the fire (location, size) and will start the sound alarm or will announce the person in charge of taking the decision for evacuation. The order of events in case that the fire services are noticed prior to starting the (organised) alarm corresponds to the situation presented in Figure 7. However, there maybe situations in which the sequence is in reverse order. First decide to start the evacuation before notifying the fire department via 112. Reason could be people in a specific building being exposed to higher risk than general buildings such as building containing dangerous substances. This is the reason why they have to evacuate as quickly as possible. The order of these two moments during the fire scenario is not very important. It may only influence the order of the next moments. For example, if first the fire brigade is notified and then the organised evacuation is announced, it may be more probable that the fire rescue services will arrive at the scene of the accident before the evacuation ends. However, these influences and probabilities are not discussed at this stage of the research, but they will be analysed in more details in the future.

Cases 3 and 4 are related to the other source of uncertainties, namely the state of evacuation initiated by self reliance at the moment the fire brigade arrives. Until the start of the intervention of fire fighters, all the people inside the building are self-reliant. When the fire fighters help some of he people to reach a safe place, those people are not self reliant anymore. However, there may by people inside the building that continue their evacuation without help from the fire brigade. Therefore, the emergency self-reliance and rescue can coexist when fire fighters arrive at the scene of the accident before the evacuation ends. Although this is the case, all measures to increase self-reliance focus on the period before the fire services arrive. Cases 3 and 4 show the difference between the self-reliance behaviour of people and being rescued by fire fighters.

- Case 3: It may happen that the evacuation is not yet finished when the fire services arrive. Evacuation may takes longer time from different reasons (people with difficulties to walk, elders, children, or the difficulty to find the way out). In this case, the first task of the fire brigade is to control the fire until the evacuation ends. In the same time, they may help some of the people to evacuate (Figure 7, case 3). Hence, one unit of the fire brigade has as task to rescue the people and another to control the fire. After the evacuation finishes, all units at the scene of the accident can start to fight the fire. In this case, when the fire fighters take control of the evacuation, part of the self-reliant behaviour of people inside the buildings end.
- Case 4: On the other hand, if the fire units are ready for intervention at the scene after the evacuation has ended (Figure 7, case 4) they can start directly to fight the fire. In this case, the control part of the fire is missing, as well as the possibility to help people to evacuate. All the people inside the building reached a safe place using their own forces and the means existing inside the building at the moment when the fire started, so they all manifest self-reliant behaviour.

## PRELIMINARY RESULTS: USING THE INTEGRATED MODEL FOR DISASTER MANAGEMENT RELATED STUDIES

In this chapter, the usefulness of the integrated model, presented in Figure 7, for disaster management related studies will be shown on the basis of two running projects. One of the themes of Delft University of Technology’s Risk Centre is ‘Disaster Management’. Within this theme, a research program is ongoing to investigate the possibilities of improving the response to an emergency situation. This program now includes two projects. The first project in this research program aims to develop a model in order to estimate the outcome of a fire in a public building. For this, all other important factors that influence the outcome of a fire have to be identified and included into a network, in order to use the BBN approach. The second project that is part of this theme is a PhD project called ‘Compliance Theory and Evacuation,’ which aims to investigate how human behaviour in evacuation situations (see the evacuation line in Figure 7) can be influenced. This project determines what kind of information should be given to motivate people to comply with the instructions to start evacuating and what media should be used to warn and inform people in an emergency situation. The outcome of this second project will contain data on the use of emergency alarm systems based on conventional measures and new technologies. An example of the latter is the use of mobile phone technology as an informative emergency warning system. In the next two sections the use and lessons for the dynamic model for the two PhD projects will be discussed.

## Building the BBN network

In recent years there has been a general tendency for fire regulations to be changed from the prescriptive codes to the performance-based regulations (Richardson, 1995), which allow more flexible and innovative designs and lead to more cost-effective structures. In order to assess the performance of a design, the people in charge of taking decisions at different stages of the design process need a tool to compare the alternatives and to chose those that ensure (with a certain probability) the smallest damage.

For a decision regarding the safety of people in a building in case of fire, all the processes taking place during the fire, as well as the factors influencing these processes and the interactions between them have to be taken into consideration (Brannigan et al., 1996). However, modelling a fire in a building, together with the evacuation of people and the fire fighting activities is a difficult task since there are multiple dependencies between these processes and the course of one of them at any moment of time depends on the courses of the others. The classical analysis methods, Event Tree and Fault Tree, cannot be applied if a complex model is desired, mainly because they assume a chronological or causal order of events, so a linear representation of the processes and their interactions (Andrews & Moss, 1993; Kumamoto & Henley, 1996; Vesely et al., 1981). While Fault Trees and Event Trees have demonstrated to be useful tools for analyzing complex technical systems when certain events must occur in order for other events to occur, following linear time order, they fail to adequately represent the uncertainty with respect to causal relations in a complex system like an emergency situation in case of fire in a building. This major disadvantage of the Event Tree and Fault Tree approaches is solved by the Bayesian belief net (BBN) method.

The BBNs are, by definition, directed acyclic graphs representing high dimensional uncertainty distributions (Jensen, 1996, 2001). They consist of nodes and arcs: the nodes represent random variables and the arcs represent influences between variables. In the human damage model, a random variable (thus a node) is associated with each factor that influences the fire outcome. The big advantage of BBNs is the ability to model uncertain events taking into account the dependencies between them. Hence, while the Event Tree and Fault Tree approaches represent the events in a linear order, using the BBN approach, simultaneous multiple influences on one variable are possible.

Building up a model based on the BBN approach, starts with defining the graphical structure of the network. For this sake the important factors that have to be included and the causal relations between these need to be found. There is need for a good understanding of the whole system, of the processes taking place within the system, as well as of the interactions between them while constructing the causal structure of the model.

In order to build up a model for estimating the human damage produced by a fire in a building using the BBN approach (Hanea & Ale, 2005), first attempt to collect the factors to be included into the network was to interview experts in the field. The interviews resulted in a large list of factors. However, these are so called *basic factors*, meaning that between these factors and the top event, the outcome of the fire in a building, there are other factors missing (Hanea, 2005). The missing factors are, in fact, the processes taking place during the fire. The connection between basic factors and the processes taking place is made through the model presented in the previous section.

The use of the dynamic model presented in Figure 7 fill in the understanding of the connection between the three processes and the basic factors collected from experts. Moreover the interactions between the three processes are understood. Based on the information gained using the dynamic model and the factors given by experts in their interviews, the structure of the network is built, starting from the top event to bottom (basis factors), with the three processes as intermediates.

In building up the network, the top event is first defined. For human damage model, the top event is the percentage of people inside the building who dies during the fire. The connection between the basic factors and this top event is made mainly through three nodes representing the three important processes taking place during the fire inside the building. The three nodes are: (individual) rescue safety egress time (*RSET*), available safety egress time (*ASET*) and the *arrival time of rescue services*. Based on the discussions from the previous section, the influences between these nodes look like in Figure 8. Each of these nodes can be developed further and the factors that influence them can be added, until a desired level of details is reached. The *RSET* node, for example, is influenced by four other nodes: *detection time*, *alarming time*, *response time* and *moving time*. The *RSET* is in fact the sum of these fore nodes. Moreover, based on the discussions of the four cases presented in the previous section, it can be concluded that the *arrival time of rescue services* influences the evacuation time through the *moving time*. Figure 9 shows the structure of the network at this point, which is only part of the larger net used to estimate the outcome of a fire in a building. The larger BBN model contains nodes influencing all four time components of RSET as well as the ASET and the arrival time of rescue services.

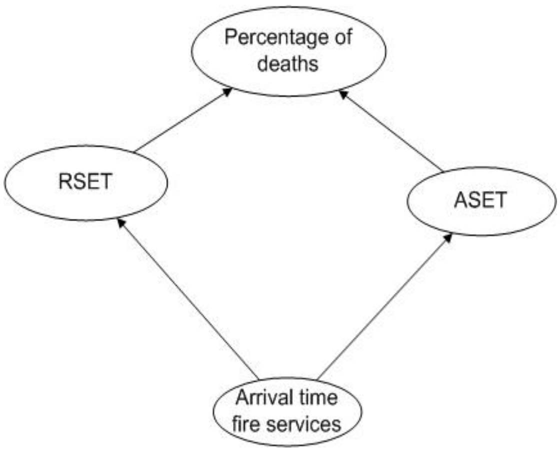


Figure 8: Human damage model: schematic representation

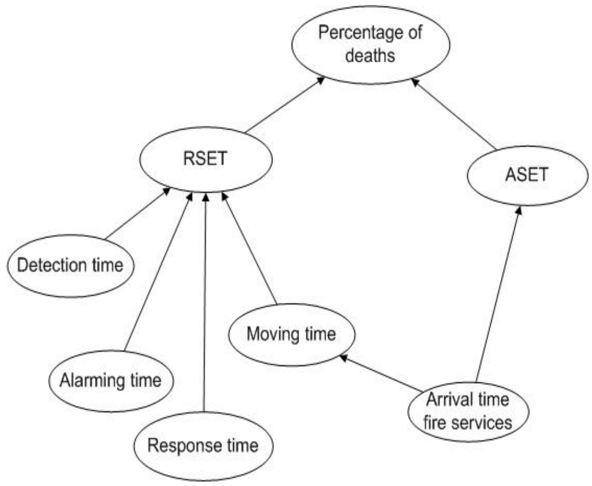


Figure 9: Human damage model: partial model

The development of the partial model from Figure 9 is based on the information about the three processes as well as on the information about how the self reliance of the people inside the building can be influenced. The use of the three processes and their interactions is important in order to obtain an estimation of the fire outcome as realistic as possible. This approach differs from the method to asses the level of fire safety of a building by computing independently the ASET and RSET of that building and then comparing these values: if ASET is larger than RSET, the building is judged safe.

As has been discussed in the previous section, the ASET and RSET are not independent, but they depend mainly on the *arrival time of rescue services* and, consequently, on all the factors that influence this node. All these nodes are called common nodes or factors. There may be some other common nodes, for example those related to the size of the compartment, which influence both the moving time (larger the compartment, longer the distance to exit, so larger the moving time) and the time when critical conditions (i.e. ASET), meaning a certain temperature or a certain height of the smoke layer, are reached. However, there is uncertainty regarding the values of all nodes, hence also of those that are common and it is important to know how this uncertainty influences the final outcome of the fire. The BBN approach can propagate the uncertainty in the basic factors through the network, to the nodes of interest. These nodes are nodes on which decisions about, for example, building constructions are taken. Therefore, considering all the three processes presented in the previous section an understanding their interactions and their common causes is important for a better estimation of the outcome of the fire, hence for a better decision regarding the safety of people inside the building.

### Determining the factors "people reached" and "response tendency"

The PhD project "Compliance theory and evacuation" focuses on decreasing the duration of the pre-movement phase, the phase in an emergency situation before people actually start evacuating. The evacuation time and the number of people that respond and the speed with which they respond depend on the medium that is used to warn and instruct occupants during the organised alarm. All these phases can be found in the model in Figure 7. This project studies how people can be motivated to start evacuating immediately when they are ordered to do so. It consists of two parts. First, people have to be reached by the warning message or instructions. Reaching people that need to be warned influences the pre-movement time, because people need to be triggered before they can start to evacuate. Results from this part of the project can be used to construct the BBN factor "people reached" which is part of "alarming time" shown in Figure 9. Next, people have to act upon the information that they received. The behavioural response tendency following a warning message is very important, because after people received a warning message, it still needs to convince them of the need to start evacuating immediately. The information resulting from this part of the project can be used for constructing the BBN factor "response tendency", which is part of "response time" in Figure 9.

This PhD project aims at determining the effectiveness of two different mobile phone technologies (SMS and cell broadcast) as warning media. These mobile phone technologies can be used for sending text messages to a certain predefined group of people (SMS) or to people in a certain geographical area (cell broadcast). The results on this part of the research project were determined in several large projects conducted for the city of Vlaardingen in The Netherlands and for the Dutch Ministry of Interior and Kingdom Relations. These projects focussed on the possibilities of using SMS and cell broadcast as an addition to the siren that is used in The Netherlands to warn citizens in case of an emergency. The research approaches and results of this research can be found in several publications by Jagtman et al. (2006) and by Sillem and Wiersma et al. (2006; 2006; 2005a; 2005b). For the BBN factor “people reached,” this research concludes that the number of people that are not reached by the siren can be reduced substantially within 7 minutes after sending the message by using SMS. Moreover, SMS can give more information and can reach people such as the auditory impaired that cannot be reached by the siren. For cell broadcast, a more specific and more relevant group of people can be reached, but the number of people reached at the *current* state of technology was found to be smaller than the cases in which SMS was applied.

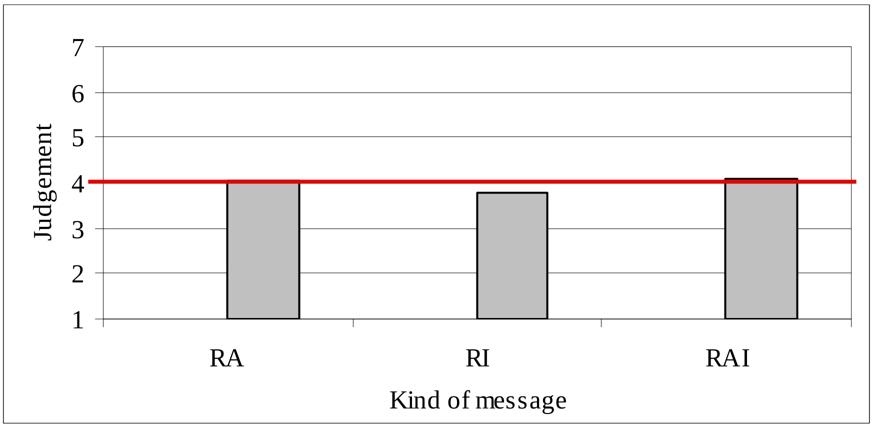


Figure 10: Judgement content of messages (1 = much too little information, 4 = exactly the right amount of information, 7 = much too much information)

At this moment, when there is a fire in a building, most of the alarm systems only have an alarm bell sounding. Proulx and Sime (1991) showed that, in order to motivate people to get into action, it is important to give more information about what is going on. For the second factor “response tendency” a different experiment was used. Because of ethical issues it is not possible to study the “response tendency” in a real emergency. To simulate an emergency, an experiment was set up in which people had to judge several messages. The messages varied in length and content components: information about what is going on [Risk], information on what people should do [Action] and information on where people could find further information [Information]). Several combinations of both length and content components were tested. So far, the judgements of 418 people have been studied. The preliminary results show that messages shorter messaged were better understood than messages the longer messages.

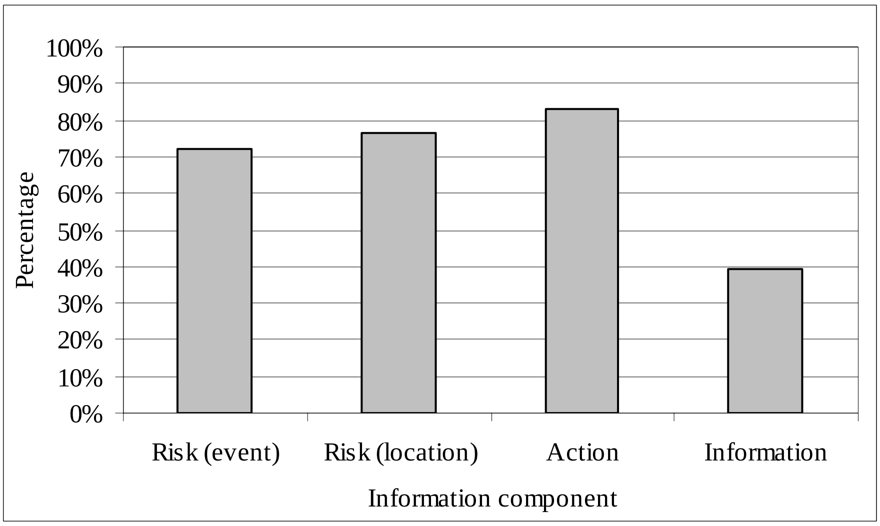


Figure 11: Information that should always be available in warning messages (N = 408)

Figure 10 shows that messages with Risk and Action, as well as messages with Risk, Action and Information are judged as being better messages than messages containing only the components Risk and Information. The differences found in judgments are significant (F = 76.121, df = 822, p = .000). This means that the *Action* component is very important for people to be able to make a judgement about that situation and on what they should do. Messages including action component trigger the recognition of the emergency situation and possibly influences the respond. This is in accordance with the data that was gathered in the questionnaire that the participants filled out after the experiment. These data show that people feel that Action is the most important component of a warning message (see Figure 11).

## DISCUSSION AND CONCLUSION

Fires are complex situations in which a lot of processes take place. Some of these processes are goal-directed and organised, such as fire fighting, some are goal-directed, but not organised, such as self-reliant activities to escape from a building, and yet others are neither goal-directed nor organised, such as the development of the fire itself. Modeling all of these processes and their relations is difficult.

This paper presents a dynamic model that describes the processes that take place in a fire in a public building combining accident process models with system models. The model links the development of a large fire in a public building with the activities of fire fighters and with the evacuation of people. The model is used in two disaster management related studies. It first assists in identifying factors for a BBN model to study the outcome of a fire in a building. The dynamic model is especially helpful to identify intermediate factors between the basic factors and the factors describing the outcome of a fire. Secondly, the dynamic model helps understanding the connections between each of these factors and the outcome of the fire. The dynamic model includes two sources of uncertainty of the order of events. The BBN approach can handle uncertainties, since it does not model a fixed order of events. After quantification, the propagation of uncertainties, relating to the four explained cases, to factors determining the outcome of a fire can be analysed. A second study focuses on the evacuation process, which is one of the three processes in the dynamic model. This study shows some results on possible influences within the evacuation process using text based warning systems. The first results show the importance of describing the appropriate action in a warning text to trigger recognition of the evacuation situation.

The second study not only focuses on fires in buildings but on all kinds of emergency situation in which evacuation is required. The structure of the dynamic model presented is not only applicably for fires in buildings, but can be also translated to other types of disasters. A model analogous to the one presented in this paper can be developed for other types of disasters, for example flooding, and for other stakeholders, for instance local governments and police authorities. Most important steps to gain a model for another disaster management related field are: determining relevant processes in the specific field, determining known interrelations between the processes, and addressing uncertainties in events and order of events. General processes that need to be included are related to: the course of the emergency (e.g. fire, flood, positing or collision), appropriate actions related to individuals who may be affected (e.g., evacuation, antidotes or first aid treatment) and tasks related to emergency services relevant for the given emergency situation (e.g., ambulance staff, policemen, salvage companies). One may consider including interference of governmental authorities such as closure of areas, route direction or property protection.

This paper shows that a dynamic model can be composed, in which the interrelation between processes related to fire in a public building can be modelled. The concept of the dynamic model can be extended to other disaster studies. Such a dynamic model can provide a useful structure to study frame research projects in these area and especially pinpoint the sources of uncertainties in the occurrence of events and the order in which events occur during a disaster.

## REFERENCES

Andrews, J. D., & Moss, T. R. (1993). *Reliability and Risk Assessment*: Longman Harlow.

Association, I. F. S. T. http://www.ifsta.org/

Babrauskas, V., & Peacock, R. D. (1992). Heat release rate: The single most important variable in fire hazard. *Fire Safety Journal* **18**(3): 255-272.

Bandura, A. (1986). *Social foundations of thought and action*. Englewood cliffs, New Jersey, USA: Prentice-Hall.

Bellamy, L. J., & Geyer, T. A. W. (1990). *Experimental programme to investigate informative fire warning characteristics for motivating fast evacuation*. Watford, UK: Building Research Establishment; Fire research station.

Benthorn, L., & Frantzich, H. (1996). *Fire alarm in a public building: how do people evaluate information and choose evacuation exit?* Lund, Sweden: Lund Institute of Fire Safety Engineering, Lund University.

Bradburn, C. (2004). The new fire regulations - A challenge for building engineers. *Building Engineer* **79**(3): 12-13.

Brannigan, V., Smidts, C., & Kilpatrick, A. (1996). Regulatory requirements for performance based codes using mathematical assessment. In C. A. Franks & S. Grayson (Eds.), *Proceedings INTERFLAME'96* (pp. 621-630): Interscience Communications Ltd., London, England.

Canter, D., Powell, J., & Booker, K. (1988). *Psychological aspects of informative fire warning systems* (building research establishment No. br 127). Herts, UK: Building research establishment.

CBS. (2004). *Brandweerstatistiek 2003*: Central Bureau voor Statistiek - Facilitair Bedrijf.

Chitty, R., & Fraser-Mitchell, J. (2003). *Fire Safety Engineering - a reference guide*: BRE Bookshop.

Davis, D. (2001). Intervention strategies: When systems fail. *Fire Engineers Journal* **61**(210): 21-24.

Drysdale, D. (1985). *An introduction to fire dynamics*. Chichester.

Friedman, R. (1992). An international surevey of computer for fire and smoke. *Journal of Fire Protection Engineering* **4**(3): 81-92.

Hale, A. R., & de Kroes, J. (1997). 10 years of the chair in safety science at the delft university of technology. *Safety Science - Summa Summarum* **26**(1-2): 3-19.

Hale, A. R., & Glendon, A. I. (1987). *Individual behaviour in the control of danger*. Amsterdam: Elsevier Science Publication.

Hanea, D. M. (2005). *Estimating the extent of a fire in a building.* Paper presented at the The Research Agenda of Risk and Design Anno 2005, Delft, Netherlands.

Hanea, D. M., & Ale, B. J. M. (2005). *Estimating the statistical distribution of human damage produced by a fire in building using Bayesian beleif nets.* Paper presented at the 2005 ASME International Mechanical Engineering Congress and Exposition, Orlando, Florida, USA.

Jagtman, H. M., Wiersma, J. W. F., & Sillem, S. (2006). *Implementation issues on citizens alarming using mobile phone technology.* Paper presented at the PSAM8, New Orleans, USA.

Jensen, F. V. (1996). *An introduction to Bayesian networks*. New York: Springer.

Jensen, F. V. (2001). *Bayesian networks and decision graphs*. New York: Springer.

Keating, J. P. (1982). The myth of panic. *Fire Journal*: 57-61.

Kjellén, U., & Larsson, T. J. (1981). Investigating accidents and reducing risks: a dynamic approach. *Journal of Occupational Accidents* **3**(2): 129-140.

Kumamoto, H., & Henley, E. J. (1996). *Probbilistic risk assessment and management for engineers and scientiests*. Piscataway, New Jersy: New York, IEEE Press.

Lin, Y.-S. (2005). Estimations of the probability of fire occurrences in buildings. *Fire Safety Journal* **40**(8): 728-735.

MacDonald, G. L. (1972). *The involvement of tractor design in accidents* (No. Research report 3/72). St Lucia: Department of Mechanical Engineering, University of Queensland.

Olenick, S. M., & Carpenter, D. J. (2003). An updated international survey of computer models for fire and smoke. *Journal of Fire Protection Engineering* **13**(May 2003): 87-110.

Proulx, G. (2000). http://irc.nrc-cnrc.gc.ca/pubs/ctus/43_e.html [May 23rd 2005]

Proulx, G., & Pineau, J. (1996). *Differences in the evacuation behaviour of office and apartment building occupants.* Paper presented at the Human Factors and Ergonomics Society.

Proulx, G., & Sime, J. D. (1991, july 1991). *To prevent 'panic' in an underground emergency: why not tell people the truth?* Paper presented at the Proceedings of the third international symposium on fire safety science, Edinburgh, UK.

Quarantelli, E. L. (2002). Sociology of panic. In N. J. Smelser & P. B. Baltes (Eds.), *International encyclopedia of the social and behavioural sciences* (pp. 11020-11023). Oxford, UK: Elsevier Science Ltd.

Ramachandran, G. (1985). *Exponential model of fire growth.* Paper presented at the First International Conference on Fire Safety Science, Washington DC.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science* **27**(2-3): 183-213.

Richardson, J. K. (1995). *Selected Readings in Performance-Based Fire SAfety Engineering*.

Sillem, S., Jagtman, H. M., Wiersma, J. W. F., & Ale, B. J. M. (2006). *Using cell braodcast in citizens warning: characteristics of messages.* Paper presented at the PSAM8, New Orleans, USA.

Sillem, S., & Wiersma, J. W. F. (2006). *Comparing Cell Broadcast and Text Messaging for Citizens Warning.* Paper presented at the ISCRAM2006, Newark, USA.

Sillem, S., Wiersma, J. W. F., & Ale, B. J. M. (2005a). Acceptance of SMS as a tool for alarming the population. In D. de Waard, K. A. Brookhuis, R. van Egmond & T. Boersema (Eds.), *Human Factors in Design, Safety and Management* (pp. 187-200). Maastricht, The Netherlands: Shaker Publishing.

Sillem, S., Wiersma, J. W. F., & Ale, B. J. M. (2005b, November 2005). *Human behavior in evacuating a building: a problem definition.* Paper presented at the IMECE2005, Orlando, FL, USA.

Sime, J. D. (1990). The concept of panic. In D. Canter (Ed.), *Human behaviour in fires*. London: David Fulton Publishers Ltd.

Vesely, W. E., Goldberg, F. F., Roberts, N. H., & Haasi, D. F. (1981). *The fault tree handbook* (No. NUREG 0492).