A RISK-BASED FIRE AND RESCUE MANAGEMENT SYSTEM

A Thesis submitted to Liverpool John Moores University for the degree
of Doctor of Philosophy

The author declares that the work is the result of his own independent investigation,
except where indicated

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To my children Benny, Matty, and Luka, my wife Matilde,

and my parents.

ABSTRACT

This PhD focuses on developing a risk-based fire and rescue model for dwelling fires which importantly, is where most fire deaths occur each year. There are a vast number of variables to consider when modelling dwellings, for example variations will arise in terms of geographical location, fire safety arrangements, characteristics of occupants, activities of occupants, among others. As for the occurrence of fire itself, each incident will be unique in terms of time of day, type of fire, state of occupants, fire cues, *etc.* What all these variations signify is that the potential magnitude of the next fire event and its consequences are generally unpredictable. Because of complicated scenarios, unpredictability of outcomes, and high frequency of incidents, Fire and Rescue Services (FRS) have to be both capable and flexible in operation; however finding the optimal way of providing emergency cover and minimizing risk is a complicated task which often results in reasoning and decisions taking place under uncertainty. In order to diminish some of this uncertainty and improve confidence in decision making, an extensive four-part Bayesian Network (BN) model is developed focusing on dwelling fires within the UK. The intention is to model the sequence of events which may occur during a fire from ignition through to extinguishment with the objective of assessing, under specified conditions, fire safety at a given location; this should assist in determining what the most important safety issues are for the purpose of improving fire prevention and mitigating consequences in order to reduce fire risk across residential communities. The model itself is broken down into four parts which can function independently or together as an integrated network. The model parts are as follows:

Part I - "Initial fire development".
Part II – "Occupancy response and further fire development".
Part III – "Advanced fire situation and consequences".
Part IV – "Fire response time module".

Within the project a risk-based fire and rescue operations management framework is also presented to demonstrate how the BN model could fit into the strategic management of FRS's and how it could link up with other tools and data collection programmes. The BN model may prove to be useful for strategic decision making within FRS's.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practical
BAFSA	British Automatic Fire Sprinkler Association
BN	Bayesian Network
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
ER	Evidential Reasoning
FIRS	Fire Incident Response Simulator
FMECA	Failure Modes and Effects Criticality Analysis
FRAM	Fire Risk Assessment Map
FRR	Fire Resistance Rating
FRS	Fire and Rescue Service
FSA	Formal Safety Assessment
FSEC	Fire Service Emergency Cover
GUI	Graphical User Interface
HAZID	Hazard Identification study
HazMat	Hazardous Materials
HAZOP	Hazard and Operability study
HDE	Hugin Decision Engine
IMD	Index of Multiple Deprivation
IRMP	Integrated Risk Management Plan
LLAR	Low Level of Activity Risk
LSOA	Lower layer Super Output Area
M	Million
m	Minute
MACC	Mobilising and Communication Centre
MAUT	Multiple Attribute Utility Theory

MCA	Maritime and Coastguard Agency
MCDM	Multiple Criteria Decision Making
MFRS	Merseyside Fire and Rescue Service
MSOA	Middle layer Super Output Area
MW	Mega Watt
P.C.	Personal Communication
RTC	Road Traffic Collision
SA	Sensitivity Analysis
SOA	Super Output Area
SRT	Search and Rescue Team
TDA	Training and Development Academy
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution

CHAPTER 1 – INTRODUCTION

SUMMARY

The first chapter of this thesis presents the reasons for and the foundations upon which the research is built. Following some key definitions, the research scene is set by outlining the current fire situation in the UK. The issues surrounding fire are discussed and the motivation and reasons for the project set forth. To clarify how these issues will be dealt with the research aim and objectives are subsequently presented. Some important points regarding the general methodology and the scope of the research are provided to give the reader a clearer picture of what can and cannot be achieved. The structure of the thesis is provided outlining the theme of each chapter and how the work interrelates.

1.1 DEFINITIONS

There are several key words/phrases used in risk assessment and fire and rescue services which are referred to within this thesis. These words/phrases are defined below to assist the reader:

Technical definitions:

- Accident: an unintended event involving fatality, injury, property loss or damage and/or environmental damage (Wang and Trbojevic, 2007).
- Consequences: The effects of an undesired event such as fire, usually measured in terms of people (fatalities and injuries), assets (damage to property and contents), the environment, loss of business, damage to reputation, and so forth.
- Cost-benefit analysis: The systematic and analytical process of comparing benefits and costs in evaluating the desirability of a project or programme – often of a social nature (Mishan and Quah, 2007).
- Decision making: Deciding what action to take; this typically involves choice between options. The object of problem solving is usually a solution, answer, or

conclusion (Adair, 2010). Decision making can also be defined as the process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made from among them (Harris, 1998).

- Hazard: A physical situation or condition with the potential for human injury, damage to property, damage to the environment or some combination of these (Henley and Kumamoto, 1992).
- Risk: A combination of the probability of occurrence of an undesired event and the degree of its possible consequences, or a term which combines the chance that a specified undesired event will occur and the severity of the consequences of the event (Wang and Trbojevic, 2007).
- Risk assessment: A comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (British Standards Institution, 1991; cited in Wang and Trbojevic, 2007).
- Safety: The freedom from unacceptable risk from harm (Furness and Muckett, 2007).
- Uncertainty: A kernel element of risk represented by plural outcomes and their future likelihoods (Kumamoto and Henley, 1996). Sources of uncertainty derive from data, system definition, and prediction (Wang and Trbojevic, 2007).

Fire and rescue definitions:

- Appliance: A fire engine. These can be classed as primary pumps, support pumps, hazard pumps, rescue pumps, and combined platform ladder pump. All are capable of firefighting but have different types of equipment for dealing with specific incidents.
- Fire and Rescue Service (FRS): Government supported organizations providing protection to the public from fires, hazardous materials, floods and other circumstances. Their primary role is to reduce the likelihood of fires and provide emergency response if they occur.

- Flashover: a sudden transition to a state of total surface involvement in a fire of combustible materials within a compartment (Perry, 2003).
- Smoke: the product of combustion, consisting of fine particles of carbon carried by hot gases and air (Perry, 2003).

Geographic definitions in terms of fire and rescue services:

- District: Each sub-region (see below) is divided into districts. The Merseyside sub-region is divided into five districts.
- Lower layer Super Output Area (LSOA): A nationally established distribution of similar sized population areas with fixed boundaries on which various measurements and data collection programmes are undertaken.
- Region: The largest geographical area in terms of fire and rescue management. The Northwest is one of twelve regions within the UK.
- Sub-region: Each region is divided into sub-regions and managed in terms of fire and rescue by an individual FRS. Merseyside is one of sixty one sub-regions within the UK.

Other definitions:

- Dwelling: A building or place of shelter to live in. In this research a dwelling refers exclusively to a house or bungalow.

1.2 PROJECT BACKGROUND

Every year fires in the UK kill around 400 people and injure a further 14,000 (Communities and Local Government, 2010a). In England alone the annual cost of property damage and indirect losses from fire is in the region of £1.5 billion while the cost of emergency response to incidents is £1.8 billion. If the cost of deaths and injuries are taken into account, then the total economic loss from fires rises to £3.3 billion per year which equates to roughly 0.36% of Gross Value Added (this measures the contribution to the economy of each individual producer, industry or sector in the UK) (Communities and Local Government, 2011c). To combat losses from fire, the UK government takes a series of actions which include legislative measures, fire safety regulations, codes and standards, provision of fire cover, and public education campaigns. Central to most of these actions are FRS's; inherently their management and operations are vital for maintaining high standards of fire safety throughout the UK. This research will aim to develop applications to assist FRS's preserve or improve this position.

Since the end of World War II the provision of emergency fire-fighting services in the UK has been based primarily on the density of the built environment (Peace 2001), although in recent years there has been a greater focus on risk (C. Scarth, J. Kellaway, R. Pritchard, personal communication [P.C.], interview at MFRS, 2009). These arrangements have been effective in reducing the impact of fires in city centres, typically characterised by having high numbers of public buildings. The downside of this strategy has been that some residential suburban and rural areas have been under-provided for; significantly the vast majority of deaths from fire occur in domestic properties (Yang *et al.*, 2006; Communities and Local Government, 2010a). Although firefighting effectiveness has improved over time, shortfalls such as these support the need for change in the way FRS's are set-up in order to provide equally effective cover for everyone regardless of where they are located. Moreover, the effectiveness of the FRS's is also being challenged by having to provide for communities that grow not only in size but also in complexity. Advancements in technology now permit the accommodation of large populations within relatively small city spaces; furthermore buildings are often intertwined with roads, railway lines, industrial premises, and other potentially hazardous sites. It is evident therefore, that the provision of a cost-effective fire service for everyone remains a great challenge for planners and decision makers.

In recent years there has been a significant shift in the safety culture within the UK; for example, traditional prescriptive safety regimes in which set step-by-step instructions are followed, have progressively been replaced by more flexible and adaptable risk-based regimes which can be tailored to the hazards associated with a particular activity or system.

This has not gone unnoticed within the FRS's who are now moving towards a new risk-based system. Balancing the provision of fire and rescue services to serve all individuals equally requires careful allocation of resources. Literature suggests that there is a lack of a holistic risk-based management framework and appropriate supporting tools for use in the fire and rescue services (Hanea and Ale, 2009; Yung, 2008; Peace 2001; Ramachandran, 1999). The available methods in other domains may not be directly tailored for use in risk-based management of fire and rescue activities investigated in this research, taking into account the unique nature of fire and rescue operations. To address such identified research needs, in this project, a risk-based fire and rescue operations management framework will be proposed and a set of supporting tools developed or discussed in order to deploy available resources with greater effect, and to improve/optimise fire prevention, inspection, and firefighting and rescue strategies.

Much of the work conducted within this thesis is based upon the Merseyside sub-region located in the North West of England, where this research project is based. Merseyside Fire and Rescue Service (MFRS) have provided access to their systems, database, library and facilities; various experts from the service have collaborated knowledge and opinions which have been incorporated into the work. For these reasons the framework and principal model developed have been designed for application within Merseyside; it is possible however to tailor the work for other FRS's around the UK with further data collection.

Merseyside was an ideal sub-region to build and test the products of this research project. It has one of the highest rates of fires in the UK and unfortunately the highest casualty numbers (Communities and Local Government, 2011b). There are many social problems throughout its districts reflected by the fact that they contain the greatest proportion of most deprived areas in the country according to the Index of Multiple Deprivation (Communities and Local Government, 2011d). Despite this situation, MFRS is one of the best performing FRS's in the UK and they are constantly striving to improve performance.

1.3 INTRODUCTION TO THE FIRE PROBLEM

1.3.1 A short history of fire

Fire is one of the four elements of nature central to our existence. Fire supports life but can very easily take it away when out of control. Without fire, civilization would be radically different; in fact it might not even exist. Man's ability to control and harness the benefits of fire has led it to become part of our everyday existence. This in turn exposes us to a risk from fire in almost every place we go. Our relationship with fire can be summed up by the well known proverb 'Fire is a good servant but a bad master' (H. Beston, 1948; cited in Coatsworth, 2000).

Early humans discovered some of the benefits of fire, for example there is evidence that food was cooked some 1.9 million years ago, however it is unlikely fire was used in a controlled fashion until *circa.* 400,000 years ago (Bowman *et al.*, 2009). Early civilizations may have put fire to good use, but they did not know how to react when it became out of control. It was not until the third century B.C. that the first fire fighting tool was invented, a water pump attributed to Ctesibius of Alexandria. Apparently Alexandria designed some type of hand operated fire engine, similar to those in Europe and America of the eighteenth century. Following Alexandria's invention, the Greeks invented a reciprocating pump around 200 B.C. (Nolan, 1998).

Over centuries the degree to which civilizations evolved firefighting techniques varied tremendously. The Romans were probably the first to establish a group of organized firefighters, though at first based on slaves. In Europe firefighting remained rudimentary for centuries. The Great Fire of London in 1666 finally instigated changes resulting in improved firefighting within the UK; however the first municipal fire service in the world, the 'Edinburgh Fire Engine Establishment', was not created until 1824 (Kenlon, 2008). Overtime fire brigades began to appear across towns and villages throughout the UK.

The two World Wars saw without doubt the busiest times in firefighting history. Major restructuring followed this period with nationalization of the fire services. Functions and responsibilities widened and thought was given not just to firefighting, but also to fire prevention. This has gathered pace leading to the modern status of FRS's in which research is undertaken on various fronts.

1.3.2 Present day Fire and Rescue Services

FRSs today provide more emergency services than ever before. The environment in which they operate has become hugely complex in terms of having to cope with densely populated communities with different social and demographic characteristics. Prompt emergency response is more challenging with busier roads, more traffic lights, and varying degrees of property access. FRS's also have to maintain higher standards, consistently improve performance, and simultaneously reduce costs. Consequently strategic planning, operational response and incident management are now more important than ever.

1.3.3 Why address fire?

Fire has the potential to kill, damage property, and escalate into other undesired events. The manner in which it strikes is dramatic and deaths are horrific. Economically fire can be extremely costly for example loss of human life, damage to assets, environmental clean-up bills, legal bills, damage to reputation, business interruption, and so forth. Society is faced with many problems; most notorious are crime, social domestic problems and unemployment. Fire however is unique in the sense that everyone is exposed to the risk. It does not select where, when or who to attack; figures for example indicate that 5 to 8% of fatalities are children (Communities and Local Government, 2011b).

There are indeed economic and technical reasons for reducing the risk from fire, but it is also the moral duty of the government and society in general.

1.4 PROJECT RATIONALE

There is a risk of fire in every building that exists or that is to be designed, and it is accepted that complete safety from fire is an impossible goal. Risk and uncertainty however do not necessarily have to lead to uncontrollable situations that act against the wellbeing of people and progress of society and industry. Anticipation of risk and structured management improves overall safety, and may even benefit profit. Upon this background, this project investigates and proposes solutions to the issues surrounding assessment of risk on such a grand scale and the management of strategic operations which go with it.

One of the problems faced by FRS when planning prevention and response is the level of uncertainty in terms of the risk faced by communities. This risk is based upon a multitude of parameters but interpreting and modelling how they interplay remains a challenge. At present MFRS base their incident response times upon a three tier risk to life system applied to areas of equal population. This is based upon six weighted parameters (see Chapter 2 section 2.4.4.2). It may be possible to take this process further by modelling combined probabilities for the occurrence of additional parameters. This would allow higher or lower risk groups within each area to be identified.

Other forms of uncertainty exist, primarily regarding decision making / selection of the best strategy for risk reduction. For example if investment in fire prevention is to be boosted, what specifically should be done? Are more smoke alarms the solution, or are sprinkler systems; which provides the best cost-benefit solution? If response to fires is to be boosted, exactly where (at what locations) and when (during the day or night) should further support be available? These are just some of the questions which need to be addressed in order to reduce the level of uncertainty regarding operations.

It is important to highlight that FRS's are efficient and good at what they do. Excellent results are being attained given the level of resources available but more can still be done. Changing operational aspects of FRS's will ultimately depend upon being capable of reducing risk in a cost-effective way. This thesis sets out to address the issues discussed above in the context of evolving societies within the UK. Not all the questions posed are likely to be entirely answerable at this time, but the principal elements will be examined, modelled where fitting, and discussed with a view to contributing towards improvements in fire safety and future studies in this area.

1.5 RESEARCH AIMS AND OBJECTIVES

Based upon the scenario discussed above, the aim of this project is:

To develop and test methodologies that will enable UK fire and rescue organisations to move towards a more complete risk-based management regime. This will lead to improvements in both fire and rescue management and safety.

The following are the research programme objectives required to fulfil the aim:

i) Identify what the most pressing issues are in terms of fire risk reduction and investigate how risk-based operations can be utilised to address these in the UK fire and rescue sector.
ii) Develop a risk-based fire and rescue operations management framework where appropriate methods can be employed to model fire and rescue hazards as well as to make rational decisions.
iii) Review the applicability of the conventional techniques in risk assessment of fire and rescue services.
iv) Develop a flexible approach for modelling risks under uncertainties, and for risk-based decision-making.
v) Carry out case studies to demonstrate how such modelling can be used to improve fire and rescue operations.

1.6 NOTES ON THE THESIS METHODOLOGY

Each technical chapter describes the methods used to undertake each particular topic of research. In terms of the general methodology of the project, the following can be said:

- Research was scheduled and planned in line with aims and objectives.
- The first task was to undertake a literature review to gather knowledge on the subject. This included reviewing academic journals, conference papers, institutional reports, government reports, industry magazines, and so forth; personal communication with experts was also sought.
- Data and background information was gathered on MFRS and other FRS's. Sources of information were identified.
- Key contacts within MFRS were established since knowledge and opinion were required from experts.
- A general operations management framework was designed.
- Hazard identification and risk assessment steps for fire and rescue were reviewed.
- Methods for modelling fire risk within communities were considered. It was decided that Bayesian Network would prove the best method for undertaking risk assessment under uncertainty for the purpose of this research.
- Input parameters were considered and cause and effect relationships mapped.
- A conceptual diagram was put together.
- Different software packages were tested for building the model.
- The model was built, data gathered and probabilities tables constructed as presented within subsequent chapters.
- The model was verified to be working as intended.
- The model was calibrated against existing data.
- Case studies were conducted.
- Sensitivity analysis was undertaken.
- Results were presented and discussed.

1.7 SCOPE AND LIMITATIONS OF THE RESEARCH

It is important to acknowledge that there are limitations on what this research project can achieve; the project is not by any means all encompassing with regards to fire safety. Many issues still remain explored only in their infancy. The following points regarding the project's applicability have been identified in order to clarify the scope of research:

- The work conducted has been based around the circumstances for Merseyside and the set-up of MFRS. In order to apply the research products elsewhere a small number of the parameters might have to be reworked.
- The model developed is for UK dwellings. The intention was always to facilitate it being tailored to simulate other environments such as apartments and other premises but further work would be required calibrating the model.
- The model emulates single occupancy dwelling situations; however, a multiple occupancy version of part of the model is also developed. Discussion is undertaken on how other parts of the model can be expanded to cover multiple occupancy situations.
- Results produced by the model should not be taken in an absolute sense but rather as a representation of what the central fire safety issues are.
- The avenue of firefighting appliance and equipment effectiveness has not been explored. For example it may be possible to improve response times by having faster engines and firefighting efficiency through new technology or tactics.
- It is important to note that changes to the operational set-up of FRS's cannot be taken lightly since lives and properties are at stake. Public opinion and government policy in particular have a great influence upon what decisions are ultimately made.

1.8 THESIS STRUCTURE

The thesis is divided up into nine chapters which are supported by various appendices. Following this introductory chapter, an extensive literature review is conducted examining fire within society and industry, and associated research. The chapters that follow present the project's core research and model results, structured in-line with the aims and objectives set forth in section 1.5. The following paragraphs summarise the chapters contained within this thesis:

Chapter 1: Introduction

This chapter provides the background, justification, and aims and objectives of the project. The problem of fire within the context of this research is introduced. An outline of the thesis is provided.

Chapter 2: Literature Review.

The literature review is extremely important for organising and planning research appropriately. It allows the researcher to learn from and subsequently progress from previous academic / industrial achievements, but more importantly it should ensure that the research is original and meaningful. The literature review commences by examining the fundamentals of the fire, scenarios, and measures put in place to prevent and combat fires; this knowledge is important to be able to appreciate the problem that fire poses to society. FRS's and statistics are reviewed and discussed to emphasize where the prime issues lie, but also to highlight where progress has been made. The reasoning behind current fire and rescue strategies is analysed. Findings are linked to the research which follows. Finally a critical review of risk assessment techniques and research conducted into dwelling fires is undertaken.

Chapter 3: Creation of a risk-based fire and rescue operations management framework.

A risk-based fire and rescue operations management framework is proposed to espouse effective operational strategies. This should facilitate rational decision making with regards to investment in fire prevention campaigns and management of operational response based upon risk to life, property and the environment. The model developed in subsequent chapters is at the heart of the risk-based framework. Hazard identification and risk estimation techniques within the framework are also discussed.

Chapter 4: Part I of a BN model – Initial fire development

The BN technique is reviewed and the model introduced noting that it incorporates aspects from all of the five subject matters used to achieve safety from fire, namely:

- Prevention

- Communication
- Escape
- Containment
- Extinguishment

Part I of the model is developed, case studies presented, and suggestion for further research suggested.

Chapter 5: Part II of a BN model – Occupant response and further fire development.
Part II is far larger and complex than part I. Much effort is dedicated at explaining the composition of the model and the way CPTs were developed. The MFRS risk methodology is incorporated into the model for analyzing the impact of emergency response times. Case studies and suggestions for further development are presented.

Chapter 6: Part III of a BN model – Advanced fire situation and consequences
The last of the three core parts of the model is developed. Outputs for the integrated model are specified and consequences of dwelling fires quantified economically. Case studies are presented and a demonstration provided of how a cost-benefit analysis could be conducted with the model results. Further development in terms of a variable occupancy version of the model is put forward.

Chapter 7: Part IV of a BN model – Fire response time module
This part of the network falls outside the core modelling of dwelling fire. The purpose here is to model FRS response time based upon various parameters such as traffic, weather, special events, and so forth. This will allow assessment of whether more or less cover is required or can be tolerated during certain times of the day or year. The fire response time module can link in with parts II and III of the network or operate in isolation.

Chapter 8: Discussion and further research

The way the research was developed and its applicability are discussed. The limitations of the work are outlined and examined. Future research ideas are proposed including some which deal with these limitations.

Chapter 9: Conclusions

The contributions to knowledge and research conclusions are presented.

1.9 CONCLUSIONS

The project background and fire safety problems have been introduced. Basic concepts and ideas have been discussed in developing the rational of the research pointing out that there is a degree of uncertainty with regards to how multiple parameters interrelate to influence risk throughout communities. Upon this background the aims and objective of the project are presented. Some important notes are made regarding the general methodology and limitations of the study. Finally an outline of the thesis content and its structure are presented.

CHAPTER 2 - LITERATURE REVIEW

SUMMARY

A literature review covering the principles of fire, consequences, scenarios, and measures put in place to prevent and combat fires is undertaken as the basis of the research which follows. Fire and Rescue Services and statistics are reviewed and discussed to emphasize where the prime issues lie, but also to highlight where progress has been made. Findings are linked to the research which follows. A critical review of risk assessment techniques and research conducted into dwelling fires is undertaken.

2.1 INTRODUCTION

Since the end of World War II the role of the fire and rescue service in the UK has become diverse and more complicated. Simultaneously there has been a growing emphasis on improving the performance of firefighting. This has in turn led to spin-off efforts in other areas such as fire prevention and specialisation in tackling non-generic incidents. Fire services have become more engaged in research activities both from within and in partnership with academic institutions. Non-profit organisations such as 'The Institution of Fire Engineers' actively promote research and good practice in fire engineering, prevention, and extinction. Consultancy firms have also joined the research bandwagon developing applications for use in strategic planning and operational response. Today the array of fire related research topics is diverse. Significant research can be found in areas such as fire prevention, fire growth, fire spread, human reaction, response timing, firefighting tactics, scenarios (high rise buildings, tunnels, *etc.*), performance of equipment, psychological aspects of firefighting, and asset management, among others. This research collectively attempts to bring about improvements in fire safety through the construction of a model which feeds from various applications and data sources from fire and rescue services, planners, fire safety engineers, among others.

The focus of this research centres on the development of a model which brings together the most important aspects of fire safety, actual fire development, and consequences within communities. The model would be a key ingredient for risk-based management strategies aiming at improving community safety and fire response. With the model it should be possible to increase confidence in decision making processes, and manage risk-based operations with greater scientific judgement through the modelling of fire risk under uncertain conditions. In order to put into context the significance of this project, a critical review is made within this chapter on the general topic, including a précis on historical incident data, fire and rescue response performance, present day strategies, and the setting for the application of the research. As support for this chapter and to aid the general understanding of fires in relation to this thesis, Appendix 1 supplies an overview of some important topics, as outlined below:

A1.1: The principals of fires – provides an insight into the science behind fire including ignition principals and the fire life cycle.

A1.2: Classification of fires – summarises why and how fires are classified.

A1.3: Fire safety legislation – explains how legislation is applied to improve fire safety

2.2 BACKGROUND ON FIRES

2.2.1 Consequences of fire

Consequences of a fire can be examined in terms of the effects upon people, assets, environment, reputation, legal matters, *etc.* What elements are assessed and how, depends upon who is undertaking the assessment and what the implicated establishment is. For example, a chemical plant undertaking its own risk assessment is likely to examine potential consequences of an incident in terms of people, assets, the environment, reputation, and possibly legal repercussions. The analysis of consequence severity will be detailed and often quantitative for the purpose of undertaking cost-benefit comparisons which may ultimately justify decisions on safety. On the other hand some fire and rescue authorities are known to assess consequences primarily in terms of people, and to a lesser extent assets and the environment. Since FRS's have to examine entire regions it is often more practical to make this a qualitative exercise. Furthermore, it goes against the ethos of FRS's to place a monetary value on human life, even though it may be necessary for certain types of analysis. FRS's primary objective is to safeguard human life. People trapped in fires die mainly from exposure to flames, heat, smoke, or toxic fumes. Table 2.1 provides an indication of the fire effects that impact elements associated with such an event; such elements can be used for assessing the severity of consequences.

Table 2.1. Fire effects and their potential impacts.

Effect of fire	Implicated element				
	People	Assets	Environment	Reputation	Legal
Flames	x	x			
Heat	x	x			
Smoke	x	x	x		
Toxic fumes	x	x	x		x
Structural failure	x	x	x	x	x
Explosion	x	x		x	x

The following paragraphs examine briefly the main elements implicated in a fire. It is important to understand how these elements are involved in order to put the impacts of fire into perspective. This will improve the focus of this research and aid future management and decision making of operations and resources.

2.2.1.1 People

The greatest impact a fire can have is to cause a fatality. After the burning of the asset itself, the most vulnerable element is people. They are exposed to harm from all the effects of fire listed in Table 2.1. On non-industrial sites, it is rare that someone is injured or loses his/her life due to structural collapse / falling objects or because of an explosion (Communities and Local Government, 2008c). The primary sources of harm come from smoke (through suffocation and poisoning), and to a lesser extent from heat / flames.

Flames and heat – Flames are fatal because they will set a human being on fire which will burn and damage tissue until the body can resist no longer. Heat will cause a person to become dizzy and eventually lose consciousness after which they may dehydrate and die. If the air temperature is sufficiently high lungs can be irreversibly damaged causing a person to suffocate. Excessive heat may also cause conditions such as heart failure.

Flames are transferred through the growth of fire, but heat will be the primary killer. It is likely that heat will cause a person to die before the flames reach them. In an enclosed space, heat is easily transferred through convection which is the flow of hot air masses. Heat may however also be transferred through conduction and radiation.

Smoke and toxic fumes – *Smoke* consists of fine particles of carbon carried by hot gases and air, while *toxic fumes* are gases that are poisonous due to the content of certain chemicals that harm human beings and organisms in general. In a fire both of these elements will be mixed together and are therefore often referred to as simply "smoke". In this study the term smoke is used to refer to both *smoke* and *toxic fumes*.

In building fires, incomplete combustion occurs as defined in Appendix 1, part A1.2 equation (A1.2). This means carbon monoxide, an odourless colourless and poisonous gas, is produced. Furthermore materials typically involved in building fires such as plastics often contain chlorine, nitrogen and other chemicals. During combustion these materials produce toxic fumes containing hydrogen cyanide, hydrofluoric acid, and sulphur dioxide (Thomson, 2002). It has been widely documented that within enclosed environments, smoke is more lethal than the fire itself (Communities and Local Government, 2011b; Yung 2008; Perry, 2003; Thomson, 2002; Stollard and Abrahams, 1999; Babrauskas *et al.*, 1998). The lethality of smoke from fires in enclosed environments is thus significant, but this is further enhanced by various other problems associated with smoke as outlined below:

- Fires often produce large quantities of smoke.

- Smoke spreads quickly around compartments and buildings and, has been proven to move faster than people can walk. Furthermore smoke spreads easily through small openings such as those found between doors and floors.
- Particular matter within smoke reduces visibility. This will hamper escape, search and rescue.
- Smoke from building fires contains carbon monoxide which in high concentrations is lethal; in lower concentrations it affects people's ability to concentrate which will hinder escape.
- People believe flames are more dangerous than smoke but in reality the opposite is true. This can lead to a sense of false security when escaping from a fire which is not immediately upon them, however the greater danger is smoke which is more lethal and spreads faster. People may think they have a wider window of time to play with and thus may take wrong decisions such as returning to collect valuables.

In statistical terms between 1996 and 2006 gas or smoke amounted to 40% of all deaths in fires in the United Kingdom (Figure 2.1), while in 2007 the figure was 44%. The other main causes of death were burns, and the combined effect of burns and gas or smoke. Within the category "other" causes might include being crushed by objects, falling from height, heart attack, *etc.* (Communities and Local Government, 2008c).

Determining the way in which smoke might spread in buildings is itself the subject of extensive research (Gao *et al.*, 2012, Hadjisophocleus *et al.*, 2007; He *et al.*, 2002; Yung and Benichou, 2000; Babrauskas, *et al.*, 1998; Babrauskas, 1993; Peacock *et al*, 1993). Modelling the spread of smoke is usually performed by computer simulation models which use fluid dynamics and heat transfer to calculate the transport of time-dependent values of smoke spread parameters such as temperature, carbon monoxide, carbon dioxide, and soot concentrations to locations around a building (Yung, 2008). Without the application of such models it is hard to establish how smoke might spread in a building. For the purpose of this study linguistic terms such as "High" and "Low" are used to assess the spread of smoke in dwellings based on expert judgement from experienced fire crews. Essentially the spread of smoke can be judged to an extent by certain deterministic parameters such as fuel type, fuel load, and compartment geometry. There is information available on the characteristics of these parameters in dwellings (section 2.2.2). Other random parameters which determine how smoke spreads in dwellings are not possible to judge through experience. An example is ventilation conditions; these are based principally on whether windows and doors are open or closed at the time of fire, and even on whether it is a windy day. Besides the effect of wind, *buoyancy forces* and the *stack effect* also play a part in determining how smoke spreads; such science is beyond the scope of this research but the reader may refer for further information on smoke spread to Gao *et al.* (2012), Yung (2008), Bukowski *et al.* (2007), and Peacock *et al.* (1993).

Figure 2.1. Pie chart of fire incident causes of death.

2.2.1.2 Assets

An asset is anything that holds economic value and can be sold or exchanged in some way. Assets can be tangible for example a building, a house, machinery, valuables, *etc.*, or they can be intangible for example a business. Fire can destroy or damage assets in many ways. Tangible items will burn and need to be rebuilt, repurchased, or replaced and this will have a cost. Intangibles like a business can lose their capacity to operate and therefore will not be able to fulfil contracts and make a profit. In the long term a business may see its share in the market drop or even suffer a loss of consumer confidence. All of the effects from fire shown in Table 2.1 can have an impact upon assets.

2.2.1.3 Environment

The term environment is used to describe the surroundings and conditions in which life thrives; this includes air, land, waterways, and organisms which form part of the food chain. Non-industrial fires will typically have a negligible impact upon the environment. Industrial fires however, can often be very large and involve the combustion of toxic material which do have an impact upon the environment; a recent example is the Buncefield oil storage terminal accident which exploded in 2005. FRS's are primarily concerned with saving life, and to a lesser extent reducing damage to assets. The environment is mostly irrelevant in this context. A chemical plant for example, is mainly a hazard because of the effect it can have upon the health of people in the vicinity, should a fire break out. Little consideration is given to the effects it can have on local wildlife. The environment would only be harmed by smoke, toxic fumes, and structural damage leading to the spillage of toxins, as described in Table 2.1.

2.2.1.4 Reputation

Reputation is often associated with companies and businesses. It relates mainly to industry and the ways in which they operate. If a fire breaks out on an industrial site and the company is seen to have caused the accident through negligence then its reputation will be damaged. Similarly if appropriate contingency measures have not been put into place or events escalate leading to explosions, questions will be asked about its safety policies which in turn will damage reputation. This can often have follow-on effects leading to the demise of a company.

2.2.1.5 Legal

Legal refers to law suits, criminal justice procedures, and other matters which need referring to a court of law. Normally after a fire, an investigation is conducted to establish the cause and any associated culpability. Various parties may be involved in the ensuing legal matters including victims, establishment owners, insurance companies, *etc.* There will be an associated cost with the proceedings and any resulting settlement. Because of this, legality is considered part of the consequences of a fire.

2.2.2 Fire location scenarios

A fire can occur almost anywhere on dry land where there is a source of fuel and potential for release of heat. Natural sources of heat are rare, for example lightning or volcanic activity; it is therefore fair to assume that most fires can be attributed to man-made activities and that they occur where man is present. In man-made environments there are numerous types of locations in which fires can occur. FRS's have come up with a set of codes to classify such locations; they refer to them as the Fire Service Emergency Cover (FSEC) incident codes. According to the FSEC codes there are three broad categories of primary fire incidents, these are set out as follows:

- Incident type 01: Dwellings. Consists simply of single dwelling houses.
- Incident type 02: Other buildings. Covers every other type of building for example hospitals, hotels, high rise flats, schools, universities, licensed premises (restaurants, pubs, clubs, *etc.*), shops, stadia, bus stations, factories, offices, industrial premises, other work establishments, among others.
- Incident type 03: Others including vehicles. Covers all types of vehicles for example aircraft, trains, caravans, motor vehicles, water crafts, *etc.* Also covers structures such as bridges, sheds, post boxes, petrol pumps, electric cables, pipelines, temporary outdoor structures (tents, portable shelters), recycling centres, among others.

The FSEC codes also contain a set of secondary fire incidents which cover fire to grasslands, outdoor structures (fences, outdoor furniture, *etc.*), wheelie bins, loose rubbish, derelict vehicles and buildings, among others. In addition the codes also cover a series of non-fire related incidents which FRS's have to attend. Figure 2.2 provides a set of photographs which illustrate how the various types of fire incidents can vary in terms of size, boundaries, complexity for firefighting, and impact to human life.

It is important to understand the location or scenario within which fires evolve in order to be able to undertake planned research. The model developed within this study focuses on dwelling fires for the reasons explained within the rest of this chapter. The model is flexible in the sense that it can be further developed or adapted to represent other types of location such as low rise buildings, small to medium size offices, and so forth. There is potential with further research to adapt the model for quite different location types such as tunnels or large public buildings.

Figure 2.2. Photographs portraying some of the differences between various types of fire incidents. Top left a dwelling fire; top right a vehicle fire; bottom left London Sony warehouse fire; bottom right grassland fire.

2.2.2.1 Dwellings: occupancy, contents and fire growth rate

As defined in section 1.1 a dwelling is a house in which people can live; the term excludes caravans, makeshift shelters, and buildings. Communities and Local Government (2010c) estimate that there are around 17.8 million dwellings in England most of which were two storey high. 95% of these were of traditional masonry or timber construction with the majority being cavity brick/block. Worryingly for FRS's about 2% have some of their rooms in a basement; this presents additional problems with escape and fire fighting. Around 1 million dwellings were vacant in 2008. Statistics regarding the occurrence of fire can be found in section 2.2.4.

Occupancy of a dwelling

Dwelling fires are the principal focus and occupation of FRS's. They are the location where the most casualties occur year on year. Arguably the two main problems with dwellings are the constitution of the contents and the behaviour of people; the latter of these is difficult to predict yet alone manage, but certain information may be known from census data and demographic reports such as the number of occupants per dwelling, the age of occupants, and occupant employment.

Within this thesis, the main model developed focuses primarily on single occupancy dwellings. Such dwellings account for roughly one third of all dwelling occupancy types (Communities and Local Government, 2010b; The Guardian, 2012; Office for National Statistics, 2012). What makes investigating single occupancy dwellings so important is that the majority of fatal fires occur at such locations (Smith *et al.*, 2008). Work by Smith *et al.* (2008) analyses population socio-demographic aspects with respect to FRS performance. In the study, strong correlations are found between fire fatality rates and single occupancy households; this is partly why the model developed in this thesis focuses on such locations.

Contents of a dwelling

Dwellings are typically filled with items that burn easily and relatively quickly such as furniture (contain foams, wood), carpets, fabrics (curtains, clothes), paper (books, magazines, wallpaper), various plastic items (toys, cables, fixings), electrical items, and so forth; Figure 2.3 provides an example of a standard room in which a variety of furniture and other items can be found.

Figure 2.3. Model of typical dwelling fuel sources.

Many of the items contained in a room will give out highly toxic fumes when burnt. These materials are located in what is essentially an enclosed compartment with one or two exits. The floor area is relatively small in comparison to the amount of material generally present. The British Standards Institution (2003, cited in Yung, 2008) has produced a table of fire load densities for various occupancies (Table 2.2). From the table it is clear that dwellings typically have a medium to high fire load density.

Typical fire growth rate in a dwelling

The rate of growth of fire is another important factor which will affect the probability of survival of occupants. The British Standards Institution (2003, cited in Yung, 2008) has produced figures of typical fire growth rates for different sites (Table 2.3). The data is given in Mega Watts (MW) which is a measure of the heat release rate; a value of 1 is typical of a fully developed sofa fire. The fire growth rate for dwellings is considered 'medium' in relation to the other locations. The difference in terms of risk to life is however noticeable from statistics with over 79% of fire deaths occurring in dwellings (see section 2.2.4.3). The reason may lie in the fact that people are often asleep in dwellings whereas at the other locations they would be awake.

2.2.2.2 Other locations

Although the focus of this study is dwellings, the model is prepared in such a way as to facilitate adaption to other locations in future research. As described in the FSEC codes, an array of other environments exist which FRS's have to manage. There is a variety of research available, modelling and discussing the issues for many of these locations. Fire in buildings / high rise buildings / complex buildings have been thoroughly studied by Yuan *et al.* (2009), Lo *et al.* (2008), Chu *et al.* (2007), Lin (2005), Zhao *et al.* (2004), Hasofer and Odigie, (2001), Proulx (1995), Beck (1987), Galbreath (1984), among others. Other location specific research includes fires in tunnels (Gandit *et al.,* 2009; Beard, 2009; Ingason and

Wickstrom, 2006; Carvel *et al.,* 2005) hospitals (McDaniel-Hohenhaus *et al.*, 2008; Beard, 1983), passenger terminals (Howarth and Kara-Zaitri, 1999), warehouses and industrial sites (Reniers *et al.*, 2007; Benichou *et al.*, 2005; Tyldesley *et al.*, 2004; He *et al.*, 2002; Markert, 1998; Woodward, 1989), and forests and grasslands (Beringer, 2000), this last location featuring research which is more applicable beyond the UK such as in Australia and the United States.

2.2.3 Fire safety

The two principal aspects to fire safety are prevention and response. These will now be briefly discussed.

2.2.3.1 Fire prevention

Fire prevention essentially means minimising the probability of a fire from happening. Within dwellings the primary cause of fires derives from human factors / behaviour, examples of which are careless cooking practices, wrongly discarded smoking items, careless use of candles, 'playing' with fire and overloading electrical sockets. Many of these issues can be tackled through public education campaigns. These problems are accidental, but there is also a criminal element to human actions through the deliberate starting of a fire, which is better known as arson. Policing and education are the best policies for reducing the frequency of arson attacks.

The secondary cause of fires arises from non-human factors such as faulty electrical products, gas cookers, and heating systems. The main way of dealing with these issues is through legislation and checking or maintenance of components by qualified people. Finally, there is a tertiary cause of fires which can be termed "act of nature"; this includes any random act of nature (*e.g.* a lighting strike or an earthquake) which can lead to fire, but such events are very rare.

2.2.3.2 Fire response

It is virtually impossible to stop fires from occurring. Consequently part of fire safety is being prepared to deal with such a situation. There are various passive and active fire protection measures which can be taken to reduce the impact of a fire. In dwellings passive fire protection might include the installation of fire doors, having fire resistant upholstery, installing an emergency escape ladder, and so forth. Active measures would include alarms (smoke and heat), sprinklers systems, and fire extinguishers. The impact from fire can also be reduced by people knowing how to react to a fire; essentially people must take the decision to escape, but they must also know which way to escape and have a 'plan B' should their escape route be blocked. People may also need to think what to do in case children are present, which phone to use to call the emergency service, and so forth. It is worth noting that most people that die in fires, do so before the fire services arrive (Process Evolution, 2010), it is thus important to plan what contingency actions to take in the event of fire.

It is worth pointing out that the majority of dwellings in the UK have at least one smoke detector installed; the problem faced by FRS's is educating people not to tamper with the devices and replace the batteries when needed. Similarly the majority of new homes today are built with doors that provide a degree of fire resistance; however the issue with these is that occupants nearly always keep the doors permanently open (McDermott *et al.*, 2010). The most effective fire response measure for a dwelling is to have a sprinkler system; the problem in this instance is the elevated cost and impracticality of installation in existing dwellings; very few homes in the UK have sprinkler systems and this is unlikely to change with only 12% having been built post-1990 (Communities and Local Government, 2010c).

2.2.4 Fire statistics in the UK

An overview of the principal fire statistics in the UK is provided in this section to bring into context the scale of services provided by FRS's. Further data and information can be found in *Fire Statistics Great Britain, 2010 – 2011* (Communities and Local Government, 2011b) and prior yearly publications.

2.2.4.1 Number of fires

Figure 2.4 gives a summary of the number of total fires and dwelling fires attended throughout the UK between 1990 and 2010; both of these are plotted against the left axis. The graph also shows the number of fatalities between 1996 and 2010, plotted against the right axis. From the graph it is evident that there is a downward trend in the number of fires from 2003 onwards, whilst the number of fatalities has been dropping since about 1997. The first piece of data indicates an improvement in fire prevention, whilst the second an improvement in fire response. Both trends provide a positive sign that fire safety is moving in the right direction. Figure 2.4 also shows the number of dwelling fires; it is difficult to visually identify any sort of trend but the raw data also indicates a drop in the number of such incidents. Dwelling fires account for around 15% of total fire incidents, a figure that has remained relatively constant over the last twenty years.

Figure 2.4. Number of fires, dwelling fires, and fatalities in the UK.

2.2.4.2 Causes of fire

The causes of fire can be broadly categorized into accidental and deliberate / arson. Figure 2.5 provides an overview of the number of primary fires by cause, where primary fires are high priority fires involving people, property and vehicles whilst secondary fires are nuisance fires including grassland, derelict buildings, bonfires and so forth. The graph indicates a clear downward trend in the number of deliberate fires. Meanwhile accidental fires have seen only a very slight fall over recent years.

There is more specific data available from Communities and Local Government (2011b and 2010a) detailing the exact cause of accidental fires within dwellings. There are too many different causes to analyse at this point. It is sufficient to say that the primary, secondary, and tertiary causes of dwelling fires are cooking appliances, other electrical appliances, and smokers' materials respectively. Other electrical appliances exclude electrical distribution and heating appliances.

Figure 2.5. Number of primary fires by cause in the UK.

2.2.4.3 Consequences of fire – fatality numbers

The number of fire fatalities and dwelling fire fatalities is given in Figure 2.6. There is a clear downward trend in both sets of data with total fatalities having fallen by 54.7% between 1996 and 2010 and dwelling fire fatalities by 54.6%. The third data set shown on the graph is the number of dwelling fires per fatality; this was obtained by dividing the number of dwelling fires by the number of dwelling fire fatalities. This gives an indication of how many fires need to occur before a fatality is registered. From the graph it is evident there has been a slight increase between 1996 and 2000 but from then onwards there has been little change; this indicates that the chance of surviving a fire should it occur has remained relatively constant between 2000 and 2010. More needs to be done to increase this ratio, that is, the chance of survival in dwelling fires. In 2010 dwelling fires made up just 16% of all fires: However dwelling fire fatalities were 79% of total fire fatalities.

Figure 2.6. Number of dwelling fire fatalities and number of fires per fatality in the UK.

2.2.4.4 Consequences of fire – economic cost

Estimating the economic cost of fire is somewhat more complex and time consuming for those compiling the data than quantifying the number of fires and determining the costs. The most recent data is for 2008 which states that the cost of fire in England was £8.3 billion, a figure similar to 2006. Annual comparisons are not straight forward due to inflation and various other factors; data is also not available for every year.

The total cost of fire is broken down into three groups (Communities and Local Government, 2011c):

- Costs of anticipation – these are protection and prevention measures undertaken to prevent fires and mitigate consequences, they include:
  - total costs of active and passive fire protection in buildings
  - resource and capital costs of training and fire safety
  - non-pay related costs
  - total insurance administration
- Cost as a consequence – these are costs associated with the damage incurred from fires, they include:
  - total cost of fatal and non-fatal casualties
  - total cost of lost business
  - costs of property damage
  - costs to victims, the police, criminal justice system and prison service
- Cost in response – these are costs of extinguishing, rescue, and clearing up after the fire undertaken by FRS's, they include:
  - FRS resource costs in response to fire-related incidents
  - capital costs in response to fire-related incidents

The estimated costs of fire in England for 2008 are given in Figure 2.7 (Communities and Local Government, 2011c). Anticipation and consequence costs are fairly similar whilst response costs are much lower.

Figure 2.7. Estimated cost of fire in England for 2008.

The cost of consequences have been broken down and presented in Figure 2.8. It can be seen from the pie-chart that the larger costs are human and property / assets which have an almost equal share of the overall consequence costs. The purpose of presenting all this data is that it will facilitate analysis and discussion in the forthcoming chapters.

Figure 2.8. Estimated cost of fire in England for 2008.

In terms of human factors, the cost for 2008 was £552 million (M) for fatalities, £780 M for serious injuries, and £70 M for slight injuries (Communities and Local Government, 2011c). There were 341 fatalities in England in 2008. From this it is possible to derive the value placed on human life by Communities and Local Government by dividing £552 M by 341; this gives £1,619,000. In other work on the cost of fire, Stevens (2008) uses the figure £1,375,000. The average of these two numbers is £1,496,884. This figure rounded to the nearest £10,000 becomes £1.5 M; for simplicity, this will be the value for human life adopted in this research project. Regarding serious injuries, Stevens (2008) quotes a figure of £155,000. Since the work by Stevens on the cost of risk from fire lies partly within realm of this research project, this value will be adopted from here on.

2.3 PROVISION OF FIRE AND RESCUE SERVICES IN THE UK

Fire and rescue services today provide more emergency services than ever before. The environment in which they operate has become vastly complex in terms of the variety of potential incidents they may have to attend. FRS's also have to maintain higher safety standards than ever before, consistently improve performance, and simultaneously reduce costs. Consequently strategic planning, operational response and incident management are now more important than ever. In this sense the UK is not alone for the same is true for many other economically advanced nations such as The Netherlands, Germany, Sweden, and the USA. Graham *et al.* (1992) provide a comparative study of firefighting setups in Britain, The Netherlands, Denmark and Sweden. Though beginning to age, much of the findings are still applicable today. The main difference between Britain and the other countries is in the make-up of personnel. 70% of firefighters in Britain are employed on a full time basis where-as in the other countries it varies between 15 and 38%. This has a big impact on the cost of maintaining the service which again in Britain is much higher. In terms of utilization, the UK's fire service is undoubtedly the busiest having to deal with a much higher number of incidents. Table 2.4 provides a summary of the key figures.

Management and operation of FRS is undertaken by region and sub-regions in the UK. There are 12 fire and rescue service regions, and 61 sub-regions; 3 sub-regions are located in Wales, 49 in England, 8 in Scotland, and 1 in Northern Ireland. Figure 2.9 provides a map of the regions and sub regions in England and Wales. The research conducted in this project was undertaken in close collaboration with MFRS who provided access to their information and data. MFRS is therefore frequently mentioned throughout the project. Merseyside is located in the Northwest region of the country which holds the sub-regions of Cumbria, Lancashire, Greater Manchester, Cheshire, and Merseyside.

Figure 2.9. FRS regions and sub-regions in England and Wales.

Each FRS sub-region is managed and operated individually within a national framework which dictates overall aims and objectives as well as certain requirements. For example all FRS's must produce a publicly available Integrated Risk Management Plan (IRMP) covering at least a three year time span which outlines individual objectives and strategy (Communities and Local Government, 2008a and 2008b). Each FRS manages fire safety within its region, operating and maintaining appliances, and employing necessary personnel within a given budget. There is cooperation where necessary between sub-regions, particularly in terms of emergency response; for example, in the event of a large scale incident or an incident on the sub-region boundary assistance is usually provided by a neighbouring sub-region. In terms of operation each sub-region has its own Mobilising and Communication Centre (MACC) (see section 2.4.3) from which calls are handled and appliances dispatched. FRS's are also free to undertake their own research and development. The resources dedicated to research and the level of cooperation with institutions of higher education and consultancy firms varies considerably from one jurisdiction to another.

2.4 OVERVIEW OF MERSEYSIDE FIRE AND RESCUE SERVICES

2.4.1 Geographical overview and assets

MFRS provide fire and rescue cover for Merseyside which consists of Sefton, Liverpool, Knowsley, St. Helens, and Wirral. These five districts have been identified on Figure 2.10; note that the map also shows the location of the fire stations via yellow dots however the names cannot be read because of size restrictions. Appendix 2, part A2.1 provides a list and map of Merseyside fire stations. In total 1.4 million people live in Merseyside distributed over 645 km^2. The sub-region is also home to the busy port of Liverpool and River Mersey, reason for which MFRS have a Marine Rescue Unit to provide rapid and effective rescue for all river users along a 60 mile coastline. MFRS manage and operate a long list of stationary and mobile assets ranging from fire appliances to fast response motorbikes. In 2011 MFRS were staffed by close to 2000 personnel, though this figure has steadily been dropping. Appendix 2 part A2.2 provides a list of MFRS assets.

Figure 2.10. Map of the Merseyside area and the location of the fire stations.

2.4.2 Types of response

MFRS have to deal with a wide variety of incidents besides fires as do many other FRS; the types of response are listed below:

- Fire fighting and rescue – This is MFRS's core service.
- Road Traffic Collision (RTC) – This has become MFRS's second most attended incident. Road traffic collisions have grown in recent years as a result of increasing volumes of traffic.

- River rescue – These services are provided by the Marine Rescue Unit which is exclusive to Merseyside. The coastguard and RN Lifeboat services do not usually enter the river Mersey unless assistance is specifically requested.
- Water rescue (from river, lake, sea surge, extreme rain) – This is undertaken by the Search and Rescue Team (SRT) team based in Croxteth.
- Urban Search and Rescue (*e.g.* building collapse) – This is undertaken by the SRT.
- Rescue from height – These incidents are dealt with by highly skilled teams.
- Hazardous Materials (HazMat) and environmental protection incident – These are attended by the specialist Hazardous Material and Response Team who can also perform firefighting duties. During the day they will be based at a station but can also be called up during the night to attend a HazMat incident. If the HazMat teams are attending a fire they can be called away to deal with a HazMat incident should this occur simultaneously.
- Other rescue – This includes vehicle and train tunnel rescue, and large animal rescue (under implementation).
- Nuclear site – nuclear sites have their own fire fighting teams. FRS's can assist if a request is made.

All response types are based on the FSEC incident codes. Fires at sea are dealt with by Mersey Docks and Harbour. Incidents within the port including vessels which are docked are attended by MFRS.

2.4.3 Mobilising and Communication Centre (MACC)

Fire and rescue response in Merseyside is coordinated through its MACC which receives and processes all emergency calls redirected from the 999 centre. The control room is staffed 24 hours a day 7 days a week and 365 days a year by a team working in four watches. Calls are received from the public via the 999 emergency number and from other emergency services such as ambulance, police, automatic fire alarms, air traffic control, *etc.*, who may require assistance.

During a 999, call information about the incident is collected and the location verified before a response is put in place. The control room must prioritize the incident with regards to any other ongoing incidents and assess whether it is a real or hoax call. The type of incident is then established for example dwelling fire, road traffic collision, hazardous spill, *etc.*, and then the nearest available suitably prepared appliance or other unit is identified and notified through MACC's Vision BOSS system; all this must be achieved in just a few seconds. The caller is normally kept on the line to obtain further details about the incident whilst the fire crews make their way to the location. The type of additional information collected might include the time in which the incident began, the number of people implicated, problems with access (*e.g.* driveway blocked in cases of dwelling fire, bridge damage in cases of flooding, *etc.*). The control room can then assess what type of additional support is required at the scene and if necessary liaise with a neighbouring sub-region FRS. MFRS's MACC receives about 67,000 calls annually (MFRS, 2012) which equates to about 184 calls per day, 8 per hour, or 1 every seven to eight minutes.

MACC's Vision BOSS system incorporates a digital mapping system which allows controllers to:

- Locate an area through a mobile telephone number.
- Identify a fixed line callers address.
- Track the location of appliances to determine which is the nearest to the incident.

Emergency responses are put in place according to MFRS's "response standards". These standards provide instruction on the number of appliances that need to reach an incident within a given time frame (see section 2.4.4.1).

2.4.4 Operations and strategy

MFRS have four corporate aims:

- Prevention and Protection: To take action to prevent fires and other emergencies whilst protecting life and property in the event of such an emergency.

- Emergency Response: To respond to all requests for emergency assistance with a level of resources appropriate to the risk.
- Business Continuity: To provide prevention, protection and post incident recovery services to businesses on Merseyside.
- Organisation: To deliver an effective, modern and learning organisation.

In 2005-2006 MFRS set a budget of £77.4 million (MFRS, 2005a) with which to achieve these aims. In that year MFRS saw its biggest change in operations in over 30 years. The basis for providing fire response cover fundamentally changed from being based upon response times. MFRS were now required to prepare and plan their service delivery on the basis of risk assessment. This new risk-based approach is described in section 2.4.4.2.

In recent years MFRS and other FRS's have struggled to secure the same level of income from Government Grants, which typically make up 70% of the budget, and Council Tax, about 29%; the other 1% is obtained from reserves. The budget for 2012/2013 is £69.7 million which is about 10% less than in 2005-2006. If inflation is taken into account the spending power of MFRS has actually fallen by far more. Consequently the service is faced with no other option than reducing personnel and asset portfolio. This makes the need for improvement in operations efficiency even higher.

2.4.4.1 Response standards

Distribution of fire stations, appliances and personnel is planned according to levels of risk established for areas of similar population within Merseyside. These areas are known as Lower layer Super Output Area (LSOA) and are actually part of a nationally established distribution of similar sized population areas with fixed boundaries on which various measurements and data collection programmes are undertaken. LSOA are part of Super Output Area (SOA) which are also split into Middle layer Super Output Area (MSOA); the make-up and number of MSOA and LSOA in England and Wales is described in Table 2.5.

MFRS's risk methodology, described in section 2.4.4.2, assigns either a "High", "Medium", or "Low" level of risk to each LSOA. The response standards in relation to fire are based on these levels of risk as follows (MFRS, 2009):

- High Risk: First attack within 5 minutes (m) with additional support within 8 to 10m.
- Medium Risk: First attack within 6m with additional support within 9 to 11m.
- Low Risk: First attack within 7m with additional support within 10 to 12m.

The performance aim is to achieve these standards on 90% of occasions.

2.4.4.2 MRFS risk methodology

As previously stated, each LSOA is assigned a risk level on which response standards are based. This risk has been estimated based on risk to life and incorporates six data sets each of which has been given a weighting according to their relevance. The risk is mapped according to LSOA producing a Fire Risk Assessment Map (FRAM). The data used is that of the previous 3 years from when the FRAM is published (MFRS, 2010). Table 2.6 provides the six data sets and the weighting factor applied. The top five of these parameters are derived from fire incident statistics. The bottom parameter is the Index of Multiple Deprivation (IMD). These indices are the Government's official measure of deprivation at LSOA level (Communities and Local Government, 2007). It brings together 37 different indicators which cover specific aspects or dimensions of deprivation. The indicators fall into the following categories: Income, Employment, Health and Disability, Education, Skills and Training, Barriers to Housing and Services, Living Environment and Crime. These indicators are weighted and combined to create the overall IMD expressed as a percentage for each LSOA. The indices are updated every three years. At the time of writing the IMD used in the creation of the FRAM was the 2007 version but this has now been superseded by the 2010 version. Further details on the IMD can be found in *The English Indices of Deprivation 2010* (Communities and Local Government, 2011d). It is worth noting that Liverpool, the home of MFRS, has the greatest proportion LSOAs in its district that are amongst the most deprived in the country (51%); in other words, Liverpool is statistically the most socially deprived area in England.

As mentioned, FRAM is constructed based on risk to life. Consequences in terms of assets, legal implications, or environmental damage are not accounted for. Highly valued buildings, for example the Liverpool Central Library, are the subject of risk assessments in which prevention is strongly the focus. MFRS appliance distribution and response is not influenced by potential asset damage.

There are a total of 905 LSOAs in Merseyside 77 of which were assessed as high risk, 443 medium risk, and 385 low risk (MFRS, 2009). Part of the modelling in this project is a function of the distribution of LSOA risk levels. The model was compiled with the latest available data at that time; however during the last few weeks of this research project a new risk map was published (May 2012) in which the distribution of risk was changed slightly. The latest distribution of LSOA risk is 73 high risk, 459 medium, and 373 low. The difference with the figures used in the modelling is given in Table 2.7. If these new figures were used the impact on the results presented in this research would be very minor, thus no update has been undertaken. FRAM 2010-2013 used in this research is presented in Figure 2.11; the latest version, FRAM 2013 is provided in Appendix 3.

Table 2.7. LSOAs by risk level in Merseyside.

Risk level	Risk map 2010-2013 LSOAs (MFRS, 2009)	Risk map 2013 LSOAs (MFRS, 2012)	Change 2010-2013 to 2013 version
High	77	73	-5.2%
Medium	443	459	3.6%
Low	385	373	-3.1%

2.4.4.3 Modelling response

MFRS invest a lot of resources into research and development, and how to optimise performance. One of the key areas under investigation is modelling how asset redistribution might affect response time to incidents. A project exists named the Incident Response Modelling Project which is dedicated to assessing how fewer or greater number of appliances at each station would affect the response time to incidents. Part of this research is conducted in collaboration with the consultancy firm Process Evolution who have built a model to run such experiments. The model is the Fire Incident Response Simulator (FIRS) and is run using the SIMUL8 Simulation Software with Microsoft Excel acting as the data input and output interface. FIRS is of commercial value, therefore there are no publically available details on the methodology. The model can be used to justify decision making regarding the redistribution of appliances, small fire units, and other assets; it provides a picture of how often the response standards would be met based on these redistributions.

One of the objectives of this PhD research is to assess how response times to dwelling incidents will affect the probability of various events occurring during a dwelling fire and therefore the risk to people and assets. The model built simulates how travel time is affected by weather, traffic, and other inputs. It is based upon the response standards described in section 2.4.4.1 with the assumption that those times are met on 90% of occasions. The model put forward in this PhD research could in theory link in with the FIRS model to provide an integrated vision of how risk might be affected by various factors besides asset redistribution. For example experiments could be conducted to see how the introduction of sprinklers into homes, combined with a reduction in a number of appliances would affect risk levels in Merseyside.

Figure 2.11. Fire Risk Assessment Map 2010-2013 for Merseyside.

2.5 PROBLEMS FACED BY FIRE AND RESCUE SERVICES IN THE UK

Cities, towns, and society in general have grown and diversified substantially in recent years. Advances in engineering and technology have led to changes in the way communities live. Increases in disposable income and globalization have brought to our doorstep more choices than ever before. There have been many benefits to society and individual livelihoods from this but also many negative side-effects have been generated. For example there has been a big increase in the use of drugs and alcohol over the last few decades. Intoxicated people are more careless, not as alert and often unconscious. Consequently the likelihood of starting a fire accidentally increases whilst the likelihood of reacting rationally decreases (Communities and Local Government, 2012; Derbyshire Fire and Rescue Service, 2012; Bruck *et al.* 2011; Reynolds, 2002). Social education campaigns and smoke alarm campaigns have helped combat these issues somewhat; indeed statistics show a reduction over recent years in the number of domestic casualties from fires (see section 2.2.4.3) but the problem remains and more can be done. Like this, there are many other problems faced by FRS's, the list below provides a comparative overview with years gone by of some of the present day problems faced by FRS's in dwellings:

- Fire prevention:
    - Drug and extreme alcohol use leading to carelessness
    - More electrical goods in homes leading to higher chance of electrical fire
    - More heating devices
    - Increasing population and number of dwellings
    - Ongoing acts of arson

- Response and firefighting:
    - Greater fuel content in dwellings
    - Higher proportion of plastics and toxic materials when burnt
    - Drug and extreme alcohol use leading to slow reaction times
    - Language barriers in multicultural areas
    - Property access problems, vehicles blocking narrow driveways
    - Increases in levels of traffic

    - Increases in traffic lights and speed bumps

- FRS management
    - Funding issues
    - Changing demographic environment and demand for services

MFRS face many of these challenges. Between 2004 and 2006 the North West had the second highest rate of fire deaths in the UK and the highest number of non-fatal casualties; note the UK is divided into twelve regions (Communities and Local Government, 2008c). Between 2006 and 2008 it had the fourth highest death rate and the highest non-fatal casualty rate (Communities and Local Government, 2010a), while between 2008 and 2010 the fifth highest death rate and highest non-fatal casualty rate (Communities and Local Government, 2011b). Furthermore, as previously mentioned, the district of Liverpool contains the most deprived LSOAs in the country according to the Index of Multiple Deprivation.

In terms of other types of incidents, FRS's are becoming greatly concerned with the increasing number and severity of road traffic collisions. More vehicles and higher speeds are leading to a greater number of fatal and non-fatal casualties (R. Pritchard of MFRS, P.C., interview, Jan 2011).

2.6 RISK ASSESSMENT AND DECISION MAKING TECHNIQUES

Improving fire safety in the UK remains a prime objective for FRS's. In order to achieve this fire prevention and response operations need to become even more efficient and targeted. Advancing and tailoring risk assessment and decision making techniques for fire and rescue operations can assist in achieving this vision. In this thesis, a risk-based model is developed with a focus on dwelling fires which is where the majority of fire fatalities occur; such locations are where fire research should shift its interest towards.

The risk from fire is determined by a huge array of factors due to the innumerable possible scenarios in which fires can develop. Establishing risk either qualitatively or quantitatively can be a daunting task. Many techniques exist which can aid risk analysis in general and various studies have been conducted in the field of fire. Such studies usually home in on a particular aspect of fire situations. For example fire risk assessment for evacuees in building fires using Event Trees has been conducted by Chu and Sun (2008), and Chu *et al.* (2007), using an engineering formula by Hasofer and Beck (2000), and even using simulation techniques by Yuan *et al.* (2009), and Zhong *et al.* (2008). The most widely applied risk assessment techniques are probably Fault Tree and Event Tree analysis. This is possibly because of their step-by-step logical approach which facilitates establishing the paths that lead respectively to and from the occurrence of an unwanted event; Fault Trees apply deductive reasoning while Event Trees inductive reasoning. Both techniques have been applied in a variety of cases particularly in high risk industries such as the marine and offshore industry. There are pitfalls however to logic trees; one of these is that they cannot represent multiple parameter dependencies and cannot handle uncertainty well. Such representations could however be possible using Bayesian Network (BN). BNs are directed acyclic graphs of nodes representing parameters, each containing a conditional probability distribution. There are several advantages of using BNs over alternate approaches for example diverse data, expert judgement, and empirical data can all be combined. This is particularly useful in situations where incomplete data or no data is available, thus other forms of information can be incorporated in the network. The superiority of BNs over Fault Trees is emphasized by Khakzad *et al.* (2011) who present a paper dedicated exclusively at comparing the two techniques in safety analysis within industry; they conclude that "*BN is a superior technique in safety analysis because of its flexible structure, allowing it to fit a wide variety of accident scenarios*". BNs also provide a visual representation of what they represent and this can be a very powerful tool for formulating ideas and developing the model in itself; this is akin with other risk modelling techniques although BN is a particularly adaptable method. BNs also facilitate inference and the updating of predictions through insertion of evidence / observations into parameters; they are useful tools for dealing with situations of uncertainty. Traditional risk assessment techniques such as Fault

Tree analysis, Event Tree analysis, Failure Modes and Effects Criticality Analysis (FMECA), Hazard Operability study (HAZOP), and Hazard Identification study (HAZID), may not be suitable for carrying out risk assessment within fire and rescue services due to the high level of uncertainty. Nevertheless, such techniques may be adequate for analysis of high risk industrial fire safety largely because of the presence of well-established emergency management plans and fire extinguishing procedures. A sequential step-by-step approach may thus be suitable for modelling a generic fire event at hazardous industrial sites. As has already been mentioned, this thesis focuses on domestic dwelling fires. The aforementioned methods may not suit analysis of dwelling fires where occupants react unpredictably, are unlikely to be fire safety trained, and where there is no internal organizational responsibility or plan to support the correct management of these events. Furthermore, little hard data exists with which to perform any analysis. A study by Thompson (2011) assesses how humans react to fires; it is clear in the work that the perception of danger and the behaviour of the occupants are quite different from case to case. Numerous variables, which often intervene simultaneously, have to be accounted for when assessing the risk from fire in dwellings. In such circumstances, being able to model the mutual influences among relevant variables that determine the evolution of fire and its consequences would of benefit.

2.6.1 The fire problem to be resolved

Assessment of fire safety can be a complex task due to the many variables and potential outcomes that must be considered. At a top level, fundamental topics of fire safety include prevention, ignition causes, fire detection, communication, human reaction, fire growth / containment, emergency response, among others. Each of these topics is directly or indirectly linked to another in a cause-consequence type relationship where the outcome of one particular topic will affect that of a subsequent topic. For example, if fire detection is successful this may lead to or cause communication; if communication occurs then there may be human reaction, which may in turn lead to emergency response, and so forth. The reality of fire safety is however far more intricate and this often results in a high degree of uncertainty. When attempting to model potential fire scenarios these topics need to be examined in more detail to establish how and when they would become applicable, and more importantly what influence they would have on each other. These fundamental fire safety topics encompass a multitude of variables which influence each other in varying degrees. Taking communication as an example, this could be broken down into automated, semi-automated or manual, undertaken by a stand-alone device, a fully integrated system or even a human being. Communication could occur via sound, light or movement, and be directed at internal or external parties. The success or failure of communication could be influenced in varying degrees by factors such as language barriers, electronic or mechanical state of communication devices, and distance between source and receptor. In a similar way human reaction to a fire would need to consider elements such as the alertness, mental state, physical state, education regarding how to react in the event of a fire, and awareness of the surroundings including escape routes. Furthermore the action taken by a person may be influenced by the physical layout of the location, the number of other people present, the condition of other people present, the availability of escape routes and fire fighting devices, among other things.

The many topics involved in fire safety assessment are areas of extensive research in their own right. Fire spread studies for example can focus on building engineering and layouts namely walls, floors, ceilings, stairwells, doors, windows, air vents, number and size of rooms, fire compartments, and construction materials. Other fire spread studies will focus on fuel sources such as building contents, modelling the way the contents burn and fire spreads; this could be influenced by the location, density and properties of the contents. Many studies also focus on the effectiveness of sprinkler systems and CO_2 fire suppression systems. All this research is certainly important, but it is also necessary to be able to address collectively and in a practical way, all elements of fire safety; this is after all the unique challenge faced by the fire and rescue services. The model proposed within this thesis will attempt to link together the principal fire variables in a way that can help obtain a holistic assessment of fire safety. The model boundary definition, selection of variables, linkage of variables, and use of data, have all been conducted with great care so as to obtain an accurate yet practical tool capable of representing common fire events.

Evidence suggests that modelling processes and events which may occur during a fire is hugely complex. This is further enhanced by the fact that there are many different types of locations (*e.g.* public buildings, industrial sites, dwellings, *etc.*) and an endless number of possible fire scenarios. A fire scenario is made up of influencing variables such as ignition point, nature of fire, fuel configuration, number and location of occupants, characteristics of structure if relevant (size, escape routes, *etc.*), condition of structure (derelict, under renovation, *etc.*), ventilation, and so forth. It is evident that the fire scenario is critical in defining the outcome of a fire, a point which has been highlighted in other research such as Brannigan and Kilpatrick (2000) and Puchovsky (1995). A vehicle tunnel fire for example would present a different set of problems to that of a fire within a large building complex containing accommodation, shops, restaurants, and other amenities; similarly both of these situations would be quite dissimilar to that of a woodland fire.

In certain circumstances other influencing variables may apply such as time of day, time of year, weather, and so forth. These variables would likely affect in varying degrees, human reaction, escape, and fire and rescue efforts. Thus, all things considered, fire scenarios are simply loaded with complexity and uncertainty. The BN presented within this thesis will deal with aspects of fire safety analysis with a view to diminish some of this uncertainty and improve confidence in decision making.

2.6.2 BN impetus and previous research

One of the main characteristics of a fire incident is that there are multiple dependencies between variables pertaining to the location, people present, events, actions, *etc.* This can be demonstrated by examining a simplified case for a nighttime fire in a small block of flats. The following set of connected variables presents one possible outcome: firstly the presence or absence of a standalone smoke alarm would have a direct influence on whether a sleeping person would awaken. Subsequently the person awaking or not would influence whether the emergency services were notified promptly or tardily; this would in turn affect the time of arrival of fire crews and consequently the chances of survival of other occupants within the building. If the survival of other occupants was the focus of research then other variables could be considered, for example, the effectiveness of the sounding standalone smoke alarm. This could be influenced by variables such as the distance between other occupants and the smoke alarm, or the level of consciousness of other occupants.

Another aspect of dealing with potential fire situations is that reasoning and decisions often take place under uncertainty. This is true both from the perspectives of fire safety planning and emergency response. For example, upon discovering a fire, what would be the most important action a person could take? Would it be (a) tackle the fire, (b) check fire doors are closed (c) raise the alarm internally, (d) call the emergency services, (e) escape, or (f) assist others? The answer would depend upon the particular circumstances but would nearly always involve elements of uncertainty. The question of how effective this person's action would be in ensuring their personal safety could then be posed. The answer to such a question could be sought from a Bayesian Network constructed to model this fire situation. Having such information could further help in defining the criticality of response time by FRS's and thus assist in emergency response planning.

The BN methodology provides a fitting way in which to model the relationship between variables within a given domain through the assignment and interlinking of nodes (see Chapter 4, section 4.2 for a technical synopsis on BN). The method allows for powerful graphic representation of a situation resulting from a series of causal events. Uncertainty between the multiple dependencies of nodes is captured through the assignment of conditional probabilities. In terms of the present research project, BN can be thought of as a probabilistic approach to risk analysis which considers factors and chains of potential events, which can result in an undesired situation or condition. Further technical insight into BNs is provided in section 4.2.

One of the main uses of the BN technique is in determining outcomes under uncertainty which can then be used to bolster decision making processes. A discipline in which this method has been extensively applied is medicine particularly for diagnosis, decision of treatments, and prognosis (Smith *et al.*, 2009; Velikova *et al.*, 2009; Antal *et al.*, 2003;

Onisko *et al.*, 2001; Wang *et al.*, 1999; Spiegelhalter *et al.*, 1993; Lauritzen and Spiegelhalter, 1988). Other fields in which BN has proved useful include computer sciences (Lauria and Duchessi, 2007; Larrañaga and Moral, 2008; Bruza and van der Gaag, 1994, cited in van der Gaag, 1996), industrial safety and risk (Hanninen and Kujala, 2012; Khakzad *et al.*, 2011; Martin *et al.*, 2009; Trucco *et al.*, 2008; Kannan, 2007; Kohda and Cui, 2007), and finance (Lu *et al.*, 2009; Sun and Shenoy, 2007; Kjærulff and Madsen, 2005; Neapolitan, 2004). Within the realm of fire safety BN appears not to have been applied as widely. Nevertheless useful research has been conducted on topics such as analysis of fire protection systems (Holicky and Schleich, 2000), modelling of structures under fire (Holicky and Schleigh, 2002), human fatalities in fires (Hanea and Ale, 2009), forensic investigation (Biedermann *et al.*, 2005a and 2005b), and fire spread in buildings (Cheng and Hadjisophocleous, 2009 and 2011).

Research by Hanea and Ale (2009) examines the risk to humans in building fires within densely populated and complexly designed cities such as those within The Netherlands. The research develops a BN designed to facilitate planning with regards to building location, compartment design, fire protection systems, and evacuation, based upon modelling the percentage of fire deaths under given conditions; a reduced version of the model is presented in the paper. As with the present PhD project, Hanea and Ale provide a planning tool, though the latter's focus is on new yet to be built structures rather than existing homes and buildings. Both models overlap somewhat in considering various elements of the hypothetical fire, the environment or scenario, people present, and emergency service response. There are significant differences however regarding the elements included in the BN and how they are configured in terms of interaction with one another. For example, Hanea and Ale focus on evacuation by assessing factors such as walking speed, number of exits, distance to exits, moving time and so forth. Clearly the model is tailored to investigate buildings in which there may be many occupants. Dwellings however, are quite different in terms of layout and size and such factors would not require consideration and hence are not included in the modelling within this thesis. What appears to be lacking in Hanea and Ale's study is addressing how human decisions can affect the probability of fatality. In certain circumstances occupants may choose to fight the fire or undertake another course of action other than escape. The importance of human behaviour in dwelling fires is hence an important factor, a matter also emphasized in studies such as Thompson (2011) and Meacham (1999).

Another important piece of work relevant to the present research project is provided by Holicky and Schleich (2000) who present a BN mapped causally from fire start through to structural collapse of an office building in order to analyse fire protection systems. The network includes elements of fire detection and automatic suppression, as well as a node representing fire brigade intervention; several utility nodes are also incorporated for cost-benefit assessment. Subsequent research by Holicky and Schleich (2002) provides a further developed model focusing on the cost of structural collapse and human injury/death resulting from fire. Various decision and utility nodes are built into the network which is used to provide risk profiles for structural collapse dependent upon different safety configurations.

Work by Cheng and Hadjisophocleous (2009) on fire spread in buildings delivers a BN for modelling the spread of fire from one compartment to another. This interesting approach commences by transforming the floor plan of a building into a Directed Acyclic Graph (DAG) (see Chapter 4, section 4.2 for an explanation of DAG) with each compartment, stairwell, and elevator shaft represented by a node. Once the initial fire compartment is defined this general network is developed into a detailed model. Case studies are presented for a building with and without sprinklers. The model is shown to be useful for determining probabilities of fire spread considering different fire mitigation systems and thus could assist in planning of fire prevention strategies. However in terms of limitations the model does not factor in any time-based calculations and therefore cannot be used to determine evacuation and other influencers on risk to life. Furthermore and importantly, the potential intervention of FRS's or their equivalent is not accounted for.

Following an extensive literature search, it is conclusive that the development of BNs to assess fire safety has, as presented above, primarily focused on building fires. What is remarkable is the absence of BNs geared towards fire safety within dwellings, particularly considering the high rate of fatalities. There are notable differences between building fires and dwelling fires and this is the reason for which the conclusions drawn from studies on the former cannot realistically be applied upon the latter.

Another important gap in the application of BN within the realm of fire safety relates to the intervention of the emergency services, specifically the fire and rescue services. As highlighted in various studies (Fire Brigades Union, 2012; Communities and Local Government, 2009; Mattsson and Juas, 1997), the intervention of FRS's is of prime importance within all fire scenarios. Being able to model how the arrival time of appliances affects the outcome of a fire is crucial and hence being able to model how arrival times are affected by relevant factors is also important.

The BN model presented within this thesis examines the probability during a dwelling fire of human detection/reaction, initial fire control, and FRS intervention leading to the extinguishment of the fire. The model provides a way of setting different scenarios by adjusting starting factors and events; under each set of circumstances the likelihood of the model outcomes can be computed and compared. In essence, the model facilitates the calculation of probabilities for particular consequences during a fire including the survival probability of occupants. The purpose of this is to improve confidence in risk assessment conducted by FRS's in order to ensure timely and effective intervention by fire crews in the event of an incident. One of the problems FRS's have is that it is difficult to estimate the outcome of a fire based on past experience and statistical data. This is primarily due to the low frequency of incidents and short data records; statistical data can only be taken into account if it is relevant to present day circumstances, hence older records rapidly lose significance. Putting together estimates becomes even harder if specific circumstances are considered such as time of day, time of year (*e.g.* Christmas or other festivals), temporary construction work, weather, *etc.* Aspects of data are discussed further in Chapter 4, section 4.5.

One of the other advantages of BNs is that they can be used as decision making tools. This is achieved by incorporating utility nodes and decision nodes (or tools) into a network. The former allows economic value to be placed on particular outcomes or states of a parent node which when combined with probability produces a measure of risk in economic terms. The discrete decision node acts as a decision tool with which the outcome of different actions (decisions) can be evaluated; such a process will allow cost-benefit analysis to be performed. This application of BN was invented by Howard (Howard and Matheson 1981, cited in Charniak 1991). Networks with decision and utility nodes are referred to as influence diagrams, and are increasingly being used to model situations where decisions need to be made on monetary grounds, for example to justify the installation of additional safety measures within a system. One of the objectives of this thesis is to facilitate such decision making within fire and rescue services.

Other useful decision making methods exists besides BN, for example, Multiple Criteria Decision Making (MCDM) and Multiple Attribute Utility Theory (MAUT) which both allow decisions to be made based around multiple criteria or attributes. Essentially many hypotheses can be tested at once; for MAUT utilities can be estimated based on multiple attributes / features. Another useful technique is the Evidential Reasoning (ER) approach which allows evidence-based multiple criteria decisions to be made when criteria are quantitative or qualitative. Other decision tools include Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). AHP is a structured method for undertaking complex decisions involving multiple inputs. Options are scored and weighted criteria are applied; this permits measurement and comparisons to be made between options in order that the most suitable can be selected. TOPSIS is based upon the intuitive concept that the "*chosen alternative should have the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution*" (Bao *et al.*, 2012). The TOPSIS process is transparent making it easy to understand and thus helpful for decision makers at the managerial level. Despite wide applications of both AHP and TOPSIS the approaches sometimes suffer when human thinking is considered. Decision makers often prefer to make judgements within a range described through linguistic terms. Because of this AHP and TOPSIS have been combined on many occasions with fuzzy set theory. Fuzzy sets facilitate gradual transition between states through linguistic terms such as "definite", "probable", and "improbable". Such linguistic terms will represent numerical (crisp) values. Recent work demonstrating the application of fuzzy sets with AHP and TOPSIS is provided by Momeni *et al.* (2012), Salehi and Tavakkoli-Moghaddam (2008), and Paralikas and Lygeros (2005).

2.6.3 BN weaknesses

It is worth noting that, as with most techniques, BNs have their critics. Wang (2004) analyses and discusses some of the limitations of BNs, highlighting in particular that the Bayesian approach cannot *"combine conflicting beliefs that are based on different implicit conditions"* and cannot *"carry out inference when the premises are based different* [*sic*] *implicit conditions"*. These issues will not be discussed here but additional details may be found within Wang's paper. Further to these observations, perhaps the main disadvantage of BNs is the computational complexity which can be generated. This is because the number of permutations in the conditional probability table of a child node grows exponentially with the number of parent nodes.

There are various approaches to risk assessment and decision making within uncertain systems or environments, in which there may also be data uncertainties. All techniques have degrees of strengths and weaknesses. Sometimes efforts are made to choose the seemingly best or most widely used approach; this is not necessarily the most appropriate way of proceeding, rather it is more important to engage in a method that allows a particular line of thought to be developed to solve a particular set of issues. Whatever the problem to be solved or improvement to be made there will be a method or set of methods that will facilitate this more than others. In this particular research project, BNs are the technique developed for the reasons discussed within this chapter.

2.6.4 A short history of BN

The concept behind BN dates back to Bayes theorem which was presented in 1763. The theory, which was developed by the English mathematician Thomas Bayes, shows the relationship between one conditional probability and its inverse (see Chapter 4, section 4.2.1 for a further explanation); note a conditional probability refers to the probability of an event *A* occurring given the occurrence of another event *B*. Bayes theorem has been used for decades to compute conditional probabilities of events of interest from known probabilities (Neapolitan, 2004). According to Pearl (2000), BNs themselves date back to the early 1980s when they were developed to facilitate the tasks of prediction and abduction in artificial intelligence systems. Jensen and Nielsen (2007) however, state that BNs can be traced back at least to the work by Minsky in 1963. BNs then appear to have been introduced into the field of expert systems, traditionally viewed as a branch of artificial intelligence according to Spiegelhalter *et al.* (1993), during the first half of the eighties through work by Pearl (1982) and later Spiegelhalter and Knill-Jones (1984). Early real-world BN applications took place within the fields of medicine and artificial intelligence in the late eighties and early nineties through work such as the Munin causal probabilistic network (Andreassen *et al.,* 1987), computations with probabilities (Lauritzen and Spiegelhalter, 1988), and the Pathfinder project (Heckerman *et al.,* 1992).

2.7 FIRE SAFETY, RESCUE AND MANAGEMENT RESEARCH

Fire science and fire safety have a multitude of dimensions about which research has been conducted. If the perspective of sequence of events during a fire is taken, it is possible to study fire ignition and causes, fire development and smoke spread, detection and fire cues, human response, evacuation, effectiveness of mitigating measures such as sprinklers, fire doors, *etc.*, and firefighting response. Within each of these fields there is a plethora of research. Fire science and safety can also be examined from the perspective of locations; in this case areas of research include fires within dwellings and multiple occupancy homes, building fires, high rise building fires, forest fires, chemical and industrial fires, and tunnel fires, among various others. The techniques and models applied within each area are plentiful and varied in concept. Literature examining fires from the perspective of locations has been provided in section 2.2.2.2 *"Other locations"*. Few papers were found on fire safety and evacuation in dwelling fires which is surprising given the high rate of fatalities in comparison to other locations. There is however considerable literature regarding fire cues and mitigating measures within homes, for example Sakata (2004), Hasofer and Bruck (2004), Bruck and Brennan (2001), Yung (2000), and Thor and Sedin (1979). Further to that, specific research exists on smoke alarms (Bukowski *et al.*, 2007; Hasofer and Thomas, 2007; Parmer *et al.*, 2006; Bruck, 2001; Hasofer, 2001; Hume, 1997a and 1997b), sprinkler systems (Melinek, 1993 and 1993) and fire doors (McDermott, 2010). Aspects of fire growth, in particular flashover fires are examined by Hofmann *et al.* (2007) and Kennedy and Kennedy (2003), the former focusing on fires within children's bedrooms. Analysis of fire casualties is conducted by Hasofer and Thomas (2006), and Holborn *et al.* (2003); remarkably Holborn *et al.* point out that in a random sample of dwelling fire fatalities 50% were intoxicated with alcohol. In other work, a variety of reports mainly from FRS's and Communities and Local Government also exists about emergency response and firefighting; available academic papers on the subject address timeliness of response (Holborn *et al.*, 2004; Mattsson and Juas, 1997; Haurum, 1984), management and structure (Simpson, 2006; Lundin, 2005), and operations (Jaldell, 2005; Svensson, 2002). The particulars of risk to dwellings in rural areas are tackled by Yang *et al.* (2006), and Grant (2005).

The study of risk is often at the centre of fire science. It is important therefore to clarify the type / classification of risk being addressed in this study in order that there is no confusion between this and the analysis of consequences. Shenkir (2006) suggests that there are four classifications of risks:

- Strategic risk: includes risks related to strategy, political, economic, regulatory, leadership, reputation, and global market conditions.
- Operations risk: these are related to the organization's systems, processes, technology, and people.
- Financial risk: examples include risks from volatility in foreign currencies, interest rates, liquidity and markets.

- Hazard risk: these relate to natural disasters, accidents, and acts of terrorism or crime.

According to the above classification what is being addressed in this research project would fall into the category of "Hazard risk" since it involves the analysis of fire which is an unwanted accidental / criminal (arson) event. The consequences may be measured in terms of people, assets, the environment, legal costs, loss of business, and reputation. There are economic implications within these consequences, but this should not be confused with the above "financial risk" or "strategic risk" categories which are concerned with the impact from interest rates, markets, reputation, *etc.*

2.8 CONCLUSIONS

The fundamental fire problems have been introduced and the locations in which they occur discussed. The causes of fire and its consequences have been examined at length and the way FRS's go about categorising fires explained. It was noted that smoke from fires is actually more lethal than the fire itself because it is produced in large quantities, spreads easily, and contains a cocktail of toxic fumes. An overview of statistics about fires in the UK has also been undertaken in which it was noted that dwelling fires result in the most number of casualties, even though they only make up a small percentage of the total number of fires. The way in which FRS's and MFRS are set up to prevent and respond to fires has been summarized. The risk methodology on which MFRS's response standards are based has been explained. A critical review of risk assessment and decision-making techniques was undertaken concluding that BNs may be the most suitable method for the research to be presented. Previous applications of BNs have been discussed noting that there are research gaps regarding dwelling fire risk assessments. An overview of relevant fire safety research is also provided.

CHAPTER 3 – A RISK-BASED FIRE AND RESCUE OPERATIONS MANAGEMENT FRAMEWORK

SUMMARY

This chapter aims at delivering a risk-based fire and rescue operations management framework to establish guidelines for adopting effective operational strategies. This should facilitate rational decision making with regards to investment in fire prevention campaigns and management of operational response based upon risk to life, property and the environment; an added benefit is that costs may potentially be reduced. The Bayesian Network components of the framework will be capable of dealing with the risk associated with operations in terms of various criteria such as response time, incident type, occupancy and other particulars. The framework also incorporates hazard identification and risk estimation components; these are discussed in the context of fires within residential zones and public / industrial premises.

3.1 INTRODUCTION

Operating an organization of any size without a proper management framework is like sailing a boat without a rudder. Operations cannot be controlled unless there are established aims and objectives which govern strategy and procedures. The effectiveness and control of operations, and even possibly the survival of an organization will depend greatly upon adhering to a tailored management framework.

As explained in section 2.3 of Chapter 2, each FRS is managed and operated individually within a national framework which dictates overall aims and objectives, as well as various requirements; one of these is the individual production of an IRMP. These plans outline aims, objectives and strategy for sub-regions, and serve as a basis for managing fire safety, operations, maintenance of appliances, and the sustainment of a firefighting force within a given budget. Each FRS has its own criteria for setting response standards; within Merseyside these are set according to the risk established for each LSOA as described in section 2.4.4 of Chapter 2. The risk methodology utilized is for general application in residential zones, however it cannot be applied directly in certain areas where other types of buildings are present such as public libraries, shopping centres, hospitals, schools, *etc.* Individual risk assessments of these premises must be conducted; this is often undertaken by the owners in conjunction with MFRS who have an established risk evaluation procedure (see section 3.3.3.1).

The IRMP and supporting documents explain how the aims, objectives, assets, operations, risk assessments and performance measures tie in together. If a framework could be built around these management elements, it may prove beneficial in terms of incorporating additional processes into the strategic management of MFRS. Furthermore a framework may make the whole process easier to comprehend and discuss, facilitating the generation of new ideas. Upon this background, this chapter proposes a risk-based fire and rescue strategic operations management framework. Included within this structure is the Bayesian Network model developed in Chapters 4 to 7 along with MFRS's FIRS used for analysing response times in terms of available assets.

Having laid down a framework for risk-based strategic operations management within fire and rescue services for Merseyside, the chapter continues by examining the hazard identification and risk assessment procedure in terms of fire situations. Developing this part of the framework is important because it allows identification of the main problems regarding fires and thus forms the backbone upon which subsequent research can be developed and applied. The chapter concludes by highlighting the main benefits of the framework.

3.2 A PROPOSED RISK-BASED FIRE AND RESCUE OPERATION MANAGEMENT FRAMEWORK

FRSs are expected to maintain high levels of safety from fires for communities and industry, yet their operations must be conducted within tight budgetary limits. Delivering the aims and objectives specified through policies requires careful planning and management of resources and operations. To assist in this process strategic management of resources needs to be conducted in an ongoing and adaptive fashion. There are various pieces of literature examining risk-based management, particularly for government and public owned assets. For example within highway maintenance work has been conducted by Dicdican *et al.* (2004) and County Surveyors' Society (2004), for railway infrastructure by Ng (2008), within energy generation industries by Schneider *et al.* (2006), and for local authority asset management by Communities and Local Government (2008a). Strategic management has various aspects, for example, the management of information and data, the management of personnel and skills, the management of operations, and the management of maintenance.

In this section a risk-based operations management framework is proposed for managing key components within the operational process of an FRS; MFRS are used as the case upon which the framework has been designed. It has been built using knowledge gathered from MFRS experts as well as from information contained in various MFRS internal documents and the IRMP (see Chapter 2, section 2.3)

It is important to highlight that the framework is an enhanced version of how MFRS manage their fire and rescue operations and has not been presented in this fashion previously. The framework is considered enhanced because the research conducted in this thesis through a BN is built into the framework and feeds data into linked components such as "cost-benefit", thus improving the analytical power of those components. The BN model will also process data from components such as "FIRS model", which MFRS use to simulate response times based upon the number of appliances available; this allows further exploitation of the data through the assessment of risk within the BN. The value of the framework is in the improved capability for assessing risk for the purpose of management of operations. The framework, which consists of sixteen components, is displayed in Figure 3.1. The components and their interrelations are briefly reviewed:

Aims & policy: This component represents the overall aims and the policy of MFRS. Objectives are set out and continually reviewed through the IRMP. Standards and targets for the regions are outlined, and the strategy to achieve these established. This component feeds into the level of assets, equipment, and personnel required and the operational plan that should be established.

(I) Assets, equipment and personnel: This component represents the management of assets, equipment and personnel in which numbers of units and locations are established. It links into the operational plan and the current sub-region status.

(II) Operational plan: This embodies the medium to long-term approach that should be established with regards to the operation of fire crews and appliances. It is at the centre of the framework feeding into several other components namely prevention campaigns, current sub-region status, FRS response, BN model, and FIRS model. The operational plan will in turn be dependent upon the aims and policy of the FRS, the assessment of risk, the availability of assets, equipment and personnel, and the decision made regarding any changes. It is important to note that the framework is not unidirectional but rather a continuous management process for improvement.

Hazard identification: This component is described in section 3.3 and essentially represents the identification of relevant hazards, that is, a physical situation with the potential to cause harm. This component feeds into risk assessment.

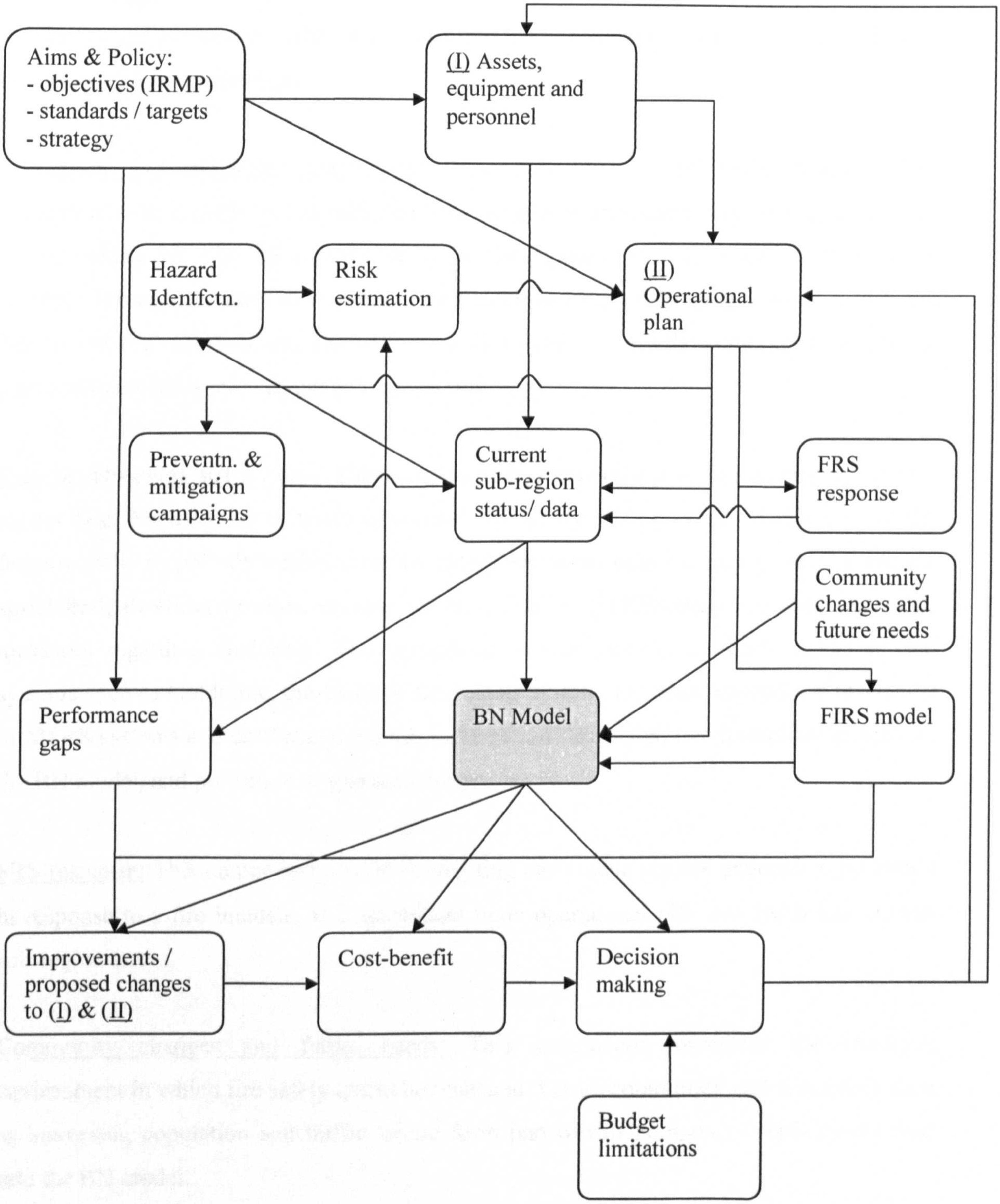


Figure 3.1. A proposed risk-based fire and rescue operations management framework

Risk estimation: This component is described in section 3.3. It represents the identification of hazards and evaluation of risk. This feeds into the operational plan where appropriate risk control measures are managed.

Prevention and mitigation campaigns: Prevention involves primarily educating the population with regards to fire safety in order to reduce the probability of accidental fires from breaking out. Mitigation covers reducing the impact from fires should they occur, for example through warning devices such as smoke alarms, firefighting measures like fire blankets or fire extinguishers, and so forth. It is dependent upon the component operational plan and itself feeds into current sub-region status.

Current sub-region status / data: This component represents the present situation of the sub-region (*e.g.* Merseyside) in terms of overall fire safety. The purpose of this part of the framework is to provide statistics on the safety measures (e.g. number of smoke alarms, sprinklers), dwelling profiles, number of fires, fatalities, FRS response times, and other measures regarding incidents. The component would incorporate FRS databases and systems such as Goldmine, the Incident Recording System, *etc.* (see Appendix 4 for details of MFRS systems and databases). All this information would link into hazard identification, the BN model, and performance gap assessment.

FRS response: This component covers firefighting and rescue actions undertaken by FRS's in response to a fire incident. It is dependent upon operational plan and feeds into current sub-region status.

Community changes and future needs: This component represents the changing environment in which fire safety has to be managed. Future community and area needs such as increasing population and traffic would form part of this component. This would feed into the BN model.

BN model: The BN model is presented within Chapters 4 to 7 and is the focal point of this research project. Essentially the occurrence of fire for particular types of locations can be modelled and the probability of loss of life and assets assessed with regards to numerous input parameters such as smoke alarms, FRS response, human actions, geographic location, building characteristics, time of day, and so forth. One of the benefits of BNs is that they can be updated as more data in fire and rescue operations is collected with time; this will permit an ongoing rolling assessment of fire safety. The model built is for dwelling fires although it could be adapted in future for application within other types of buildings. The component "BN model" is dependent upon current sub-region status, operational plan, community needs, and FIRS model. It feeds into risk estimation, improvements to assets and operational plan, cost-benefit, and decision making.

FIRS model: This component is described in Chapter 2, section 2.4.4.3. The model is used to examine the impact upon response times of redistributing appliances, small fire units, and other assets. FIRS would link up with the BN model, and suggested changes to assets / equipment and operational plan.

Performance gaps: This component describes the performance of FRS in terms of the difference between the current sub-region status and the targets that have been set. This can be measured based on number of fatalities / injuries, number of fire incidents, response times, and so on. This component feeds into suggested changes to assets / equipment and operational plan.

Improvements / suggested changes to 1&2: This component represents ideas for improving the allocation and management of assets as well as the strategic operations of the FRS. A proposed suggestion would be based upon performance gaps and requirements to improve. Careful assessment of whether these measures could go ahead or not would be required which is why this component feeds into the cost-benefit component.

Cost-benefit: This component describes the process of undertaking a cost-benefit analysis based upon suggested improvements. For example there could be a suggestion for investing in a system to operate traffic lights on route to an incident to facilitate traffic flow so that appliances could arrive at the scene sooner. The benefit that this would bring in terms of lowering the probability of fatalities would have to be measured up against the cost of implementation of such a system. The cost-benefit component feeds into decision making.

Decision making: Ultimately suggestions need to be passed or rejected based upon rational scientific judgement. Generally decisions to modify assets and operations are made based upon their economic value assessed through cost-benefit analysis. Occasionally decisions are passed for other reasons such as political or administrative ones but usually such justification is not disclosed. This component feeds into "Assets, equipment and personnel" and "Operational plan".

Budget limitations: This component represents the budget within which an FRS has to work. Decisions approving changes to operations and assets can only be made if there are sufficient resources available, even if it transpired that such changes would have a positive impact in terms of benefits significantly outweighing costs.

3.2.1 Linking-in the BN model and application of the framework

Establishing how the BN model links into FRS operations to produce a risk-based management framework is important. Essentially the components which feed into "BN model" provide data for updating the model's variables which are represented through nodes. For example, current sub-region status would provide information regarding actual FRS response times, number of smoke alarms and sprinklers, *etc.*; FIRS model would feed in experimental data regarding travel times of appliances; community needs would supply information regarding changes to housing characteristics, levels of population, traffic and so forth. The model itself would then compute the information and provide a series of probabilities and utilities / costs based upon the state of numerous interrelated variables. These outputs would supply information for the subsequent components in the framework.

Model results such as probability of fatality, injuries and property damage costs could be used to assist in cost-benefit analysis and decision making processes.

The framework proposed is risk-based meaning that risk analysis is required to configure a particular operational set-up. The process of determining risk is thus key to the framework; this is examined in section 3.3. The framework in the long term could result in a more rational and transparent regime for decision-making with regard to operations. Elements of the Formal Safety Assessment (FSA) process are contained within the structure. FSA is a standardised holistic approach for safety analysis. It was developed in 1993 originally for the shipping industry by the Maritime and Coastguard Agency (MCA). There are five sequential stages to FSA (Kristiansen, 2005):

1) Hazard identification
2) Risk assessment
3) Establish safety measures
4) Cost-benefit assessment
5) Recommendations for decision-making

The proposed risk-based fire and rescue operations management framework also fits within the fundamental process of complete risk management (Figure 3.2). In the diagram risk is addressed at distinct levels. All elements of the process are embedded within the risk-based fire and rescue operations management framework; for example *system definition* is contained within the framework component *current sub-region status*; *decision making* is covered within the framework components *decision making* linked up with *cost-benefit, budget limitations,* and *BN model.*

Having such a framework should facilitate the development of new systems and models to aid the operations management process. Clarity and transparency in management are paramount if an organization is to transmit its aims and policy to its workforce. The framework should be viewed as part of a process for continuous improvement.

Figure 3.2. A risk management process

3.3 HAZARD IDENTIFICATION AND RISK ESTIMATION

3.3.1 The need for hazard identification

Within any operation requiring safety and risk management input, one of the first and most important steps undertaken is the identification of hazards. The fundamental reasons for this are that hazards have the potential to cause harm and that they exist, in one form or another, virtually everywhere. The following are three definitions for a hazard:

- *"A situation or condition with the potential to cause harm to people, the environment, assets and reputation*" (Wang and Trbojevic, 2007).
- *"A source or situation with the potential to cause harm (death, injury, ill health, damage to property or environment* (Furness and Muckett, 2007).
- *"Possible events and conditions that may result in severity, i.e. cause significant harm"* (Kristiansen, 2005).

As part of the formal safety assessment process embedded within the risk-based framework, hazards relating to fire and rescue need to be identified and classified. The next section looks at how this might be done.

3.3.2 Hazard identification guidelines

There is an array of literature describing the hazard identification process. Many converge on the idea that there should be a 3 step procedure and in fact this is what the 'hazard identification' phase of FSA consists of, as outlined below (Kristiansen, 2005):

i. Problem definition – essentially this means defining the context of the exercise. The system must be described and the situation in which it is to operate established. In the realm of fire and rescue this would entail a description of the region under scrutiny.

ii. Hazard identification – this involves listing all possible hazards without judgement of how important they might be. The brainstorming technique involving a group of domain experts is typically used.

iii. Hazard screening – hazards which are not applicable need to be filtered out of the process. A ranking of most to least important can be undertaken. Before discarding the least important hazards it is necessary to consider if they could occur should circumstances about the system or region change.

Within fire and rescue hazards could subsequently be grouped according to occurrence time of the year, occurrence time of the day, geographical location, or other criteria. A hazard hierarchy could thus be formulated. This is essentially a list of all possible hazards sorted by situations in which they might apply and ranked in order of importance. For example not all hazards applicable to industrial sites would apply to dwellings so they would need to be separated. Subsequently hazards applicable to industry would need to be ranked and the same would be done for dwellings. The ranking process would initially be undertaken subjectively using linguistic terms such as *high, medium, low* based upon expert opinion. Subsequently other methods could be considered such as a multi-criteria and fuzzy logic based method proposed by Paralikas (2005) for the relative ranking of the fire hazards; Paralikas applies the method for chemical installations. It is however arguable if at a high level hazards should be assessed in such detail; in industry experts and workers often prefer to keep such assessments simpler so that many people can become involved in sharing their own ideas and experiences.

3.3.3 Fire risk estimation

Once hazards have been identified risk estimates can be conducted. Risk is essentially the combination of the probability of an event occurring and the severity of its impact upon people, assets, the environment, and any other affected party. Risk assessments go beyond the estimation of risk in that they incorporate risk tolerability and analysis options as defined in Figure 3.2. There are variations on the definition and process of performing a risk assessment but ultimately all must produce an estimation of risk associated with each previously identified hazard. In industry the term assessment is often used loosely. Some risk assessments stop at the point of having estimated the risk; tolerability of risk and control options are often dealt with separately. Within this research project risk assessment is assumed to include these two steps.

Fire risk assessments are generally tailored for industrial sites, work premises, and large public buildings. The purpose is to establish how likely a fire is to start, where it would most likely start, how severe could it be, who and what could be affected, what firefighting measures are available (*e.g.* sprinkles, extinguishers), and what means of escape exist. Once preventive and mitigating measures have been considered, an assessment should be undertaken of whether the risk has been reduced to an acceptable level; in industry this is often termed As Low As Reasonably Practicable (ALARP).

The process of risk estimation for housing and industry will be quite different. It is near impossible to go round every dwelling to perform individual risk estimations. What can however be done is an assessment of risk within similar housing groups and social-demographic characteristics. The FSA methodology which breaks the 'risk assessment' stage into 4 steps (Kristiansen, 2005) can be used as a guide. The BN model developed in this research could be used to assist in this process. The steps of the FSA risk assessment stage are outlined below:

Step 1: Structure logical relationships
Step 2: Structure and quantify influence diagrams
Step 3: Quantify contribution trees
Step 4: Calculate total risk of loss of life, damage to property, *etc.*

3.3.3.1 Fire risk estimation of public and industrial premises

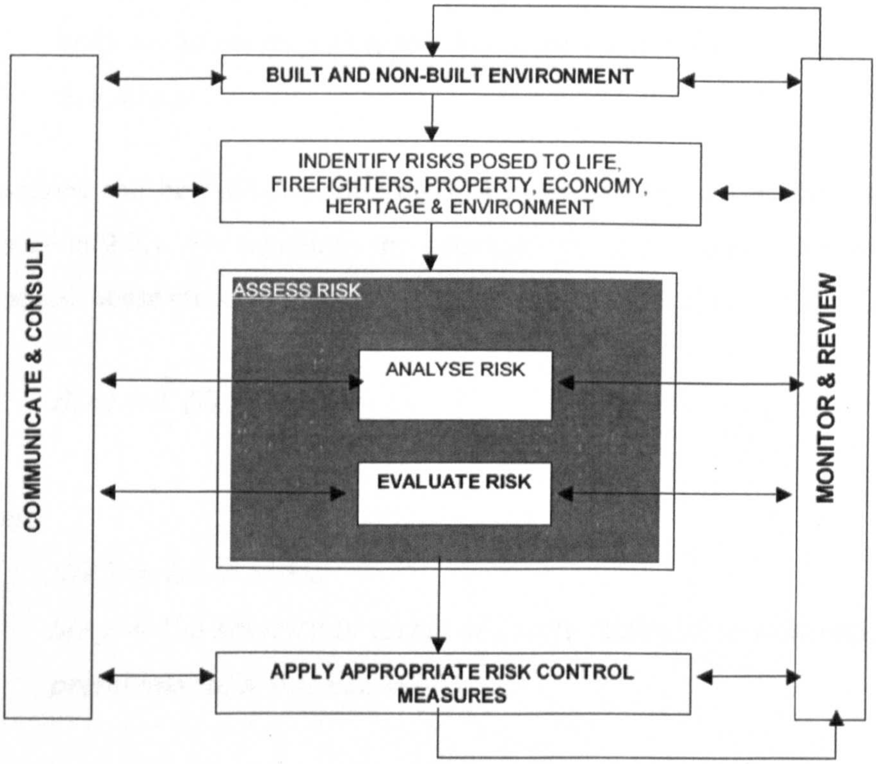
Risk estimation of public buildings, places of work, and industrial sites would be conducted slightly differently. Risk estimation and assessment processes are more methodical and the reasons for undertaking them go beyond saving human life; these reasons are outlined by Thomson (2002) as follows:

- There is moral duty by employer to show that steps are being taken to assure safety.
- There are economic reasons such as cost to business, cost of life, legal matters, *etc.*
- There is a need to comply with legislation.

As mentioned, the process of risk estimation and assessment vary from place to place according to industry practices. In terms of fire, a risk assessment would typically consist of five key steps (Furness and Muckett, 2007; Perry, 2003):

Step 1: Hazard identification
Step 2: Identify the location and determine who could be affected
Step 3: Assess the risk
Step 4: Record the findings and actions taken to reduce the level of risk
Step 5: Keep assessment under review

MFRS have their own risk management process which incorporates the above steps. The framework is given in Figure 3.3 and is similar to ones presented by the Joint Standards Australia / New Zealand Committee (2004; cited in Shenkir and Walker, 2006), Thomson (2002), Hog and Kroger (2002), and various FRS's.



Source: MFRS (2005b).

Figure 3.3. A risk management framework

3.3.3.2 Mathematical interpretation of risk

The number of fire scenarios depends on the number of permutations that can be constructed based on all the fire protection measures that are in place and all the fire events that are anticipated. The proper construction of fire scenarios is the key to a credible fire risk assessment. Risk to people in a fire can thus be quantified and expressed in monetary units through the following equation according to fire scenarios:

$$R(P) = \sum_{i=1}^{n} (P_i * S(P)_i) \tag{3.1}$$

where:

$R(P)$ = *risk to people*

Σ = *the aggregation of all fire scenarios*

P_i = *the probability of fire scenario i*

$S(P)_i$ = *the severity in terms of people (number of fatalities, injuries) of fire scenario i*

Similar equations can be built for other consequences of fire such as those described in Chapter 2 section 2.2.1. For dwellings the consequences of risk could also include assets and legal impacts, these risks could be expressed as equations (3.2) and (3.3) respectively:

$$R(A) = \sum_{i=1}^{n} (P_i * S(A)_i) \tag{3.2}$$

where:

$R(A)$ = *risk to assets*

$S(A)_i$ = *the severity in terms of assets (damage to property, insurance premiums) of fire scenario i*

$$R(L) = \sum_{i=1}^{n} (P_i * S(L)_i) \tag{3.3}$$

where:

$R(L)$ = *legal risk*

$S(L)_i$ = *the severity in terms of legal costs (court costs, settlements) of fire scenario i*

Total risk for a dwelling fire could then be quantified by the summation of equations (3.1) to (3.3), giving equation (3.4):

$$R = R(P) + R(A) + (R(L) \tag{3.4}$$

Similar equations could be built for the environment and reputation if desired.

3.3.3.3 Mapping risk

Risk estimation can be undertaken for a sample of dwellings representing similar dwelling types (*e.g.* terraced, bungalows, *etc.*) within areas of similar social-demographic characteristics. The BN model would be useful for completing such a process. Risk could be computed from the model by multiplying the value of life by the probability of fatality during a fire based upon the characteristics of the group of dwellings. This value would then be multiplied by the frequency of dwelling fires in the area to give a value of risk in economic units. The results could then be mapped against MFRS's FRAM risk map score for the corresponding LSOA in which the group of houses lies. An example of what such a graph might look like is provided in Figure 3.4. The y-axis provides the risk computed for each group of similar dwellings in UK Pounds and the x-axis the group's risk map score according to the LSOA in which it is located. In the example 7 sample groups belong to low risk LSOAs, 7 to medium, and 7 to high. The LSOA risk map score is computed by MFRS following the methodology presented in section 2.4.4.2 of Chapter.

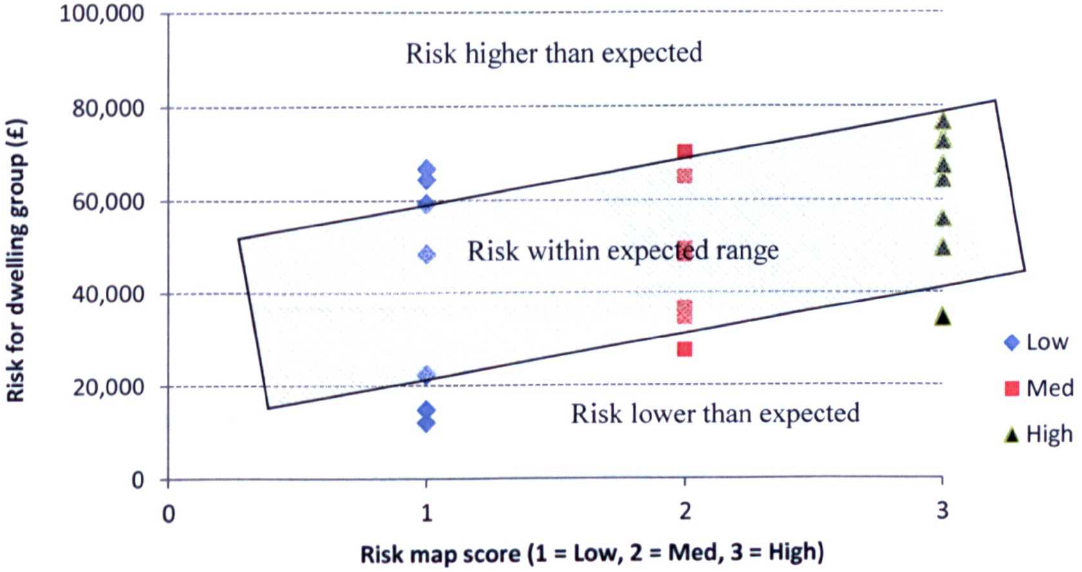


Figure 3.4. Plot of risk for sample dwelling group against risk map score.

The risk estimated for the each sample group of dwellings can either be higher or lower than an expected middle range (shown on Figure 3.4 by a grey rectangle). If any group of dwellings falls above the expected range then an FRS should investigate why this is so and take action on how to reduce the risk. For example it may be that the risk of a certain group of dwellings is high because very few dwellings have smoke alarms installed. The action taken would be to visit homes to install smoke alarms and educate people about their importance. Another course of action could be to rebalance the distribution of appliances between groups of dwellings with a higher than expected risk with those with a lower than expected risk. The FIRS model could be used to simulate the impact upon travel time of relocating appliances. Figure 3.4 is akin to the ALARP diagram (Figure 3.5) in the sense that the risks above the ALARP zone are not tolerable and therefore require further risk reduction measures.

Figure 3.5. ALARP diagram.

3.4 CONCLUSIONS

A risk-based fire and rescue operations management framework has been proposed to assist in strategic decision making of FRS operations including the prevention of fires and response to incidents. MFRS is used as the founding block upon which the framework has been built. There are sixteen components to the framework including the BN model presented within this research and the FIRS model currently operated for MFRS which simulates the impact upon appliance travel time and the risk map score, based upon reallocation of appliances. The framework also serves to demonstrate how the BN model could fit in with the risk-based management of MFRS operations. This should be viewed as part of a process for continuous improvement.

Hazard identification and risk estimation are discussed in the context of fire situations both for residential areas and public premises. A mapping process of risk for sample groups of similar dwellings against risk map scores for corresponding LSOAs is suggested. This will facilitate identification of groups of dwellings which have a higher than expected risk within an LSOA. Action to reduce this risk can subsequently be taken by an FRS.

CHAPTER 4 – BAYESIAN NETWORK MODELLING FOR FIRE SAFETY ASSESSMENT: PART I - INITIAL FIRE DEVELOPMENT

SUMMARY

This chapter introduces the concept of probabilistic modelling under uncertainty through the application of the Bayesian network (BN) technique. A model has been built to represent fire development within dwellings from the point of ignition through to extinguishment. The model is broken down into three core parts; this chapter presents part I which tackles the initial fire development and human reaction. The model incorporates both hard and soft data, delivering posterior probabilities for selected outcomes. Case studies demonstrate how the model functions and provide evidence that it could be used for planning purposes and accident investigation. Finally, following a sensitivity analysis, discussion is undertaken on how the model could be further developed to investigate specific areas of interest and how they affect dwelling fires.

4.1 INTRODUCTION

Having laid down a framework for risk-based management within fire and rescue services, chapters 4 through to 7 will now deliver the supporting model for its implementation. The present chapter focuses on developing the first part of a BN model for fire safety assessment. The intention is to model the sequence of events which may occur during a fire with the objective of assessing, under specified conditions, fire safety at a given location; this should assist in determining what the most important safety issues are for the purpose of improving fire consequence mitigation and response in order to reduce fire risk.

Discussion of the fire safety issues being addressed in this research and the rational for choosing to develop a model based on BN to confront these problems is presented within the literature review (Chapter 2), specifically section 2.6. The rest of the Chapter 4 now produces a technical synopsis on BN (section 4.2), presents the aims and structure of the complete BN model (section 4.3), develops in detail part I of the model (section 4.4), discusses data issues with the model (section 4.5), validates the model (section 4.6), develops case studies (section 4.7), undertakes a sensitivity analysis (section 4.8), outlines potential further developments of the model (section 4.9), and finally produces conclusions and a short discussion (section 4.10).

4.2 BN TECHNICAL SYNOPSIS

A BN is fundamentally a method for reasoning under uncertainty using probabilities. By definition, BNs are graphical representations of probabilistic relationships between a set of random variables. There are two basic components to BNs, the graphical structure which is the qualitative part, and the probability distribution which is the quantitative part:

i) The graphical structure. This is technically referred to as a Directed Acyclic Graph (DAG). A DAG contains a set of nodes each representing a random or chance variable which can take the form of an event, the presence of something, a measurable parameter, a latent variable, and unknown parameter or a hypothesis. Nodes are connected with each other in one-way directions by arcs or directed edges which represent the causal relationship among the variables, or in the case of none-causal networks, associations (Jensen and Nielsen 2007). DAGs are acyclic hence there cannot be cyclical relationships between nodes. Absence of an arc between two nodes means that the corresponding variables do not directly influence each other, thus they are conditionally independent.

   The relationship between nodes is generally expressed using a family notation. In a DAG with a set of nodes N in which C is the node of interest, that is $C \varepsilon N$, the source or parent nodes are those from which there is an arrow going to C, whilst the target or child nodes of C are those to which there is an arrow pointing to from C. Ancestors of C are its parents, its parent's parents, and so on; similarly descendants of *C* are its children, its children's children, and so forth. Nodes without parents are referred to as root nodes whilst nodes without children leaf nodes (Cheng and Hadjisophocleous, 2009). Figure 4.1 provides a simple illustration of a BN. In the example nodes *A* and *B* are parents of node *C*, while nodes *D* and *E* are its children. Nodes *A, B* and *C* are ancestors of nodes *D* and *E*; following this logic nodes *C*, *D* and *E* are descendants of nodes *A* and *B*. Nodes *A* and *B* are root nodes while nodes *D* and *E* are leaf nodes.

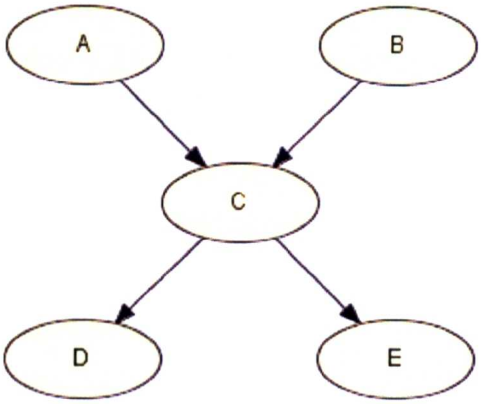


Figure 4.1. A simple BN example.

ii) The probability distribution. Each node in a DAG has a number of possible states, one of which must apply at any one time. Essentially, probability distributions indicate the strength of belief in how the state of a parent node can affect the state of its child node. A node can represent either a discrete random variable with a finite number of mutually exclusive states or a continuous random variable with a Gaussian density distribution. Examples of states of discrete nodes may be *on/off* or *red/amber/green*, while for a continuous node a temperature range or altitude. Since the state of a node is initially not known probability distributions are assigned. For root nodes a marginal probability table is defined. If the node is discrete it will contain a probability distribution over the states of the variable it represents. If the node is continuous the table will hold a Gaussian density distribution, provided through mean and variance parameters, for the variable it represents. Non-root nodes are each assigned a Conditional Probability Table (CPT). If the node is discrete each cell in the CPT will contain a conditional probability for the node being in a specific state given a particular combination of states of its parent nodes. When constructing a BN it is important to be aware that the number of permutations in a CPT grows exponentially with the number of parent nodes, thus a model can easily become complex. If a node A has n parents each with Z number of states, then there will be Z^n permutations in the CPT for each state of node A. The number of cells in a CPT will also be equal to the product of the possible number of states in the node and the number of states in each of its parent node. If the non-root node is continuous its CPT will contain a mean and a variance parameter for each combination of states of its discrete parent nodes, and a regression coefficient for each continuous parent for each combination of the states of the discrete parents (Hugin Expert A/S, 2012). The state of a node can be updated when new information or evidence is obtained. This will subsequently influence the state of other nodes; the process is referred to as *inference* and is explained in section 4.2.6.

Further definitions of BNs which support the above are provided in Appendix 5.

Since a BN is used to model a domain that contains *uncertainty* of some form, it is worth briefly defining the term. Uncertainty is a widely used word thus it must be explained in the relevant context. Hubbard (2010) presents a good definition from a risk perspective, stating that it is "*a state of having limited knowledge where it is impossible to exactly describe* [*sic*] *existing state or future outcome, more than one possible outcome*". There is a great deal of literature which addresses the problem of uncertainty. In work on fire safety design, Magnusson *et al.* (1996) elucidate that it is possible to distinguish between two types of uncertainties: "(1) *variability (aleatory uncertainty, stochastic uncertainty, randomness) in a population and* (2) *knowledge uncertainty (fundamental, epistemic) due to lack of fundamental knowledge*". The authors argue that the former dominates when determining the risk inherent in existing buildings, while the latter in cases of design situations. Meanwhile Wang and Trbojevic (2007) explain that there are three sources of uncertainty: (a) deficiencies in data; (b) deficiencies in the definition of a system under analysis, and; (c) deficiencies in consequence methodologies. Further detail on uncertainty will not be provided at this stage but the reader may wish to consult the above references as well as Chandrashekhar and Ganguli (2010), and Gegov *et al.* (2004).

As previously mentioned, BNs can be constructed to represent and solve decision problems under uncertainty. These models often include *decision* and *utility* nodes in which case they become known as influence diagrams (also described in section 4.1.2). A decision node can be added to a BN when a course of action needs to be decided upon. The addition of a utility node permits costing to be considered and hence could provide the expected cost/utility of a particular decision. Note that in influence diagrams decision and utility nodes do not represent variables.

The use of probabilistic reasoning networks has expanded into many disciplines; as such their construction and manipulation are varied. This has led to the methodology being referred to by various terms such as, Bayesian belief networks, belief networks, probabilistic networks, Bayesian networks, Bayes nets, Bayesian expert systems, graphical probabilistic networks, probabilistic causal networks, knowledge maps, and so forth. The term adopted within this PhD work is Bayesian network.

4.2.1 Fundamentals of probability theory

To further explore the application of BNs it is important to review the fundamentals of probability theory and Bayes Theorem upon which this technique is built.

Let us assume there are two events A and B within a sample space S, *i.e.*

$$S \supseteq A \text{ and } S \supseteq B$$

In order to measure the degree of uncertainty that event A will occur a probability $P(A)$ is assigned. This probability must obey the following four axioms:

Axiom 1: S contains all possible outcomes *i.e.*

$$P(S) = P(A) + P(A') = 1$$

Axiom 2: Event A cannot have a negative probability *i.e.*

For $S \supseteq A$ *it holds that* $0 \leq P(A) \leq 1$

Axioms 3 and 4: If A and B are mutually exclusive then the probability of the combined event is the sum of each individual probability *i.e.*

For $S \supseteq A$, $S \supseteq B$, *and* $A \cap B = 0$, *then* $P(A \cup B) = P(A) + P(B)$

If A and B are not exclusive then their joint probability must be subtracted *i.e.*

For $S \supseteq A$, $S \supseteq B$, *and* $A \cap B \neq 0$, *then* $P(A \cup B) = P(A) + P(B) - P(A \cap B)$

4.2.2 Conditional probability and Bayes theorem

Conditional probabilities are a fundamental part of BNs. They can be expressed in writing by statements such as "*given event B, the probability of event A is p*", which would be denoted as $P(A/B) = p$. Specifically this means that if event B occurs, and everything else is unrelated to event A, then the probability of A occurring is p. Conditional probabilities form part of the joint probability $P(A \cap B)$ statement, expressed as:

$$P(A \cap B) = P(B/A) \cdot P(A) = P(A/B) \cdot P(B) \tag{4.1}$$

The above is essentially another way of expressing the fundamental rule for probability calculus, which makes it possible to calculate the probability of both A and B occurring if the probability of A given B and the probability of B are known:

$$P(A/B) \cdot P(B) = P(A \cap B) \tag{4.2}$$

Bayes theorem provides a way for updating beliefs about an event given that information about another connected event is obtained. Bayes formula, shown below as equation (4.3), can be derived by rearrangement of equation (4.1); with this the probability of event A can be updated if information about event B is obtained:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{4.3}$$

Bayes theorem can incorporate more than two events, for example if a third event C is added the formula becomes:

$$P(A|B,C) = \frac{P(B|A,C) \cdot P(A|C)}{P(B|C)} \tag{4.4}$$

4.2.3 Conditional independence

If one event does not affect the outcome of another event then they are said to be independent of each other. Events A and B would be independent if $P(A|B) = P(A)$. Conditional independence applies when more than two events figure, thus, if a third event C is introduced then events A and B are said to be conditionally independent given event C if:

$$P(A/B \cap C) = P(A/C) \tag{4.5}$$

4.2.4 Network connections and d-separation

No matter how complex a BN may appear its nodes will always be linked through one of the following three types of basic connections:

i) The serial connection. This connection features aligned nodes in which the first node influences a second node, which in turn influences a third node. Figure 4.2 provides a simple three node example, in which nodes A and C are separated by node B. In this example, new information or evidence about C would influence the state of A through B and vice versa. Should however the state of node B become known, then A and C would become independent of each other according to the Markov condition (see section 4.2.5). Nodes A and C would then be said to be *d-separated* (or blocked) given B.

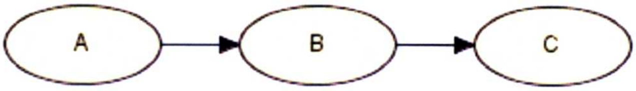


Figure 4.2. A BN serial connection

ii) <u>The diverging connection.</u> In the diverging connection, figure 4.3, all children of node *A* can influence each other unless the state of *A* is known. Thus nodes *B* and *C* are said to be conditionally independent or *d-separated* given *A*.

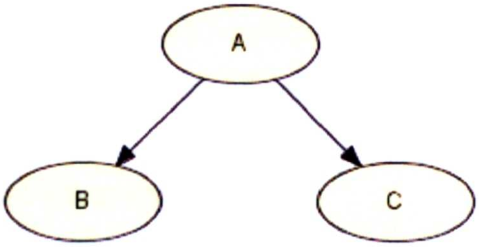


Figure 4.3. A BN diverging connection

iii) <u>The converging connection.</u> The third type of connection involves two or more parent nodes converging into a child node as shown in figure 4.4. In this case nodes *B* and *C* will influence each other if the state of node *A* is known; thus *B* and *C* are said to be conditionally dependent or *d-connected* given *A*.

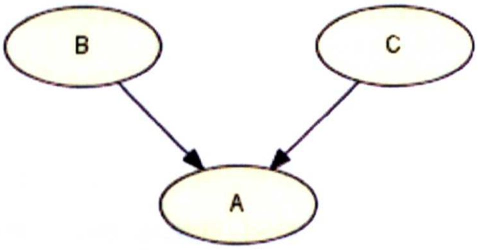


Figure 4.4. A BN converging connection

Further to the above explanation, *d-separation* can be defined as a configuration in a causal network where two variables *A* and *B* are separated, through all paths, by an intermediate variable *I*, and either of the following is true:

- The connection is either serial or diverging and the state of *I* is known, or;

- The connection is converging and the state of *I* or any of its descendents is not known.

Further information along with examples of *d-separation* is provided in Jensen and Nielsen (2007).

Understanding the way connections are made in BN has been important in ensuring logical configuration of the model presented below. *D-separation* tests have also been undertaken to demonstrate that there are no unnecessary variables in the model, *i.e.* it has been simplified according to the goals set or the focus of the investigation (see section 4.4.3).

4.2.5 Markov condition and Markov blanket

The Markov condition for a BN states that any node is conditionally independent of its non-descendents, given its parents. The Markov blanket is a set of nodes around a central node *C* which consists of the parents of *C*, the children of *C*, and any nodes sharing a child with *C*. If evidence is obtained for the Markov blanket, then node *C* becomes *d-separated* from the rest of the network; in other words a node is conditionally independent of the entire network, given its Markov blanket. This criterion can sometimes prove to be more efficient in terms of inspection of possible paths between nodes (Kjærulff and Madsen, 2005). Section 4.4.3 shows the Markov blanket for the part I of the model.

4.2.6 Inference

A BN is designed to model a space or world in which a set of variables or events are linked through probabilistic relationships; consequently BNs can be used to resolve or infer answers to probabilistic queries between variables. The way this is commonly done is by updating the state of certain variables which subsequently changes the likelihood of the states of other variables. The variables which are provided with new information are referred to as the *observed* or *evidence* variables. This practice of computing the posterior distribution of variables given evidence is typically referred to as *probabilistic inference*. There are numerous 'real world' uses of this process such as accident investigation, medical prognosis, reliability studies, and so on. In the context of fire safety this process can, for example, help ascertain the likelihood of the cause of a fire given particular evidence. Other uses within this area may include justifying the implementation of certain safety measures, as will be demonstrated through the proposed model.

4.2.7 Further reading

Further in-depth reading on BNs and probabilistic networks can be found in several books with Jensen and Nielsen (2007), and Kjærulff and Madsen (2005), providing good rounded coverage on the subject. Other books discuss the subject but concentrate on specific topics; Pearl (2000) for example, approaches the subject focusing on Causality. Another useful book is provided by Neapolitan (2004) who homes-in on Learning, a technique for building either the structure of a BN or the parameters of each conditional probability distribution. Learning has not been used to construct the model presented here thus it is not discussed further. There are also a multitude of papers covering an array of topics within the world of BN.

4.2.8 BN examples

BNs can be applied to any number of situations where probabilistic connections exist between variables. In terms of fire safety, for example, a BN could be built to represent the probabilistic relationship between casualties from fire and building safety measures. Thus, given the availability of specific fire safety measures (*e.g.* sprinkler, fire doors, alarm) a network could be used to calculate the probability of casualties in the event of a fire; figure 4.5 provides a simple example of such a network. In the example, the intervention of fire crews has also been added to provide a more complete picture. The outputs from such a model would be the nodes "Fire extinguished" and "Casualties", and their probability could be estimated based on data inserted into the other nodes within the model.

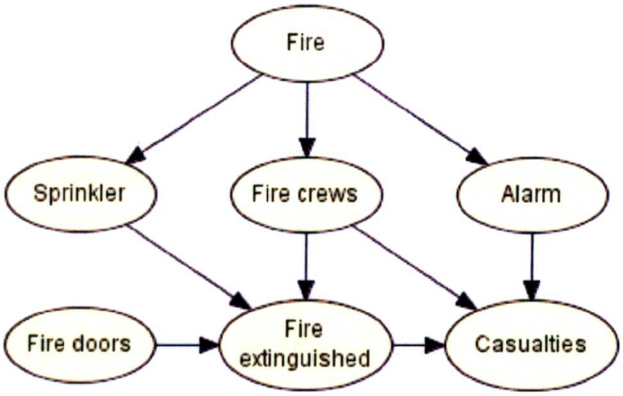


Figure 4.5. Simple example of how BN could be applied to analyse fire incidents.

Within literature, BNs are frequently demonstrated through medical situations. Networks can be very useful for computing the probabilities of various illnesses based on the background activities of the patient and the symptoms. Subsequently decisions can be made on what tests to carry out based on the likelihood of particular illnesses. Once an illness was diagnosed, BNs could again be used to determine the best treatment based on the likelihood of its success, given the particulars of the illness. Figure 4.6 provides a simple example of how a BN could be built to model a medical situation.

Figure 4.6. Simple example of how BN could be applied within medicine.

4.3 THE BN MODEL

4.3.1 Building the model

When building a BN it is important to define clearly the domain or world which it is meant to represent. Nodes and their states must be appropriately named paying close attention to what they symbolize and how they interrelate, so as to leave no room for misinterpretation. The key to building a BN capable of delivering meaningful results lies in its structure and input of data; therefore the correct linking of nodes and assignment of probability distributions is vital. With these assertions in mind, a BN has been constructed to model the process of fire in a generic single occupancy dwelling from ignition to extinguishment. If successful, the model could be later adapted to represent other types of locations such as public buildings (schools, libraries, museums, *etc.*), offices, factories, among others. The model does not include any fire frequency data at this stage since the focus was on investigating the likelihood of consequences in the event of a fire. To ensure that a sound model was built specialist knowledge was acquired by reviewing literature and speaking to experts. The model is designed to represent a fire incident in a generic dwelling; the term 'generic' is used since the model's structure and data embodies conditions from the majority of homes. The reasons for choosing dwellings as the subject matter for modelling are:

- The majority of fire deaths occur in dwellings.
- Within constructions, dwellings fires are the most frequently attended emergencies by FRS's.
- In terms of total units, dwellings are the most common construction type and therefore will have significant impact on risk maps such as those produced by MFRS.

The purpose of the model is to estimate the probability of certain events occurring given a set of starting conditions. If the probability of an event occurring is estimated then it can be used in conjunction with severity or cost data to derive the risk of that particular event. In this way the model can help determine what the most important aspects of fire safety are and thus where improvement efforts should be concentrated. Hypothetical "what-if" scenarios can be evaluated and worst case scenarios examined where applicable.

Attempting to build a model which would represent all dwellings would be impractical due to the complexity that would be generated in trying to model the remaining minority of vastly different dwellings. It is important to emphasize that dwellings vary greatly in terms of size, design, building materials, fire safety measures, location, occupancy, activities within, *etc.* (Communities and Local Government 2010b, 2010c and 2011a), and representing all of this in a single BN would not be feasible. For this reason, the BN constructed is designed around a generic dwelling, which has been formulated based on information contained within various Communities and Local Government housing reports, the characteristics of which are as follows:

- Is between 1 and 3 stories high.
- Does not have more than 1 basement level.
- Can be terraced, semi-detached, or detached.
- Houses a mean of 3 or less people per bedroom (applicable for the variable occupancy version of model, section 6.7).
- Is used exclusively as a domestic residence.
- Is primarily constructed from brick, stone, or concrete.
- Is a dwelling with 10 or less bedrooms.
- Is not a listed building.

4.3.1.1 Procedure for building each part of the model

An eleven step-by-step procedure has been defined and applied in construction of each of the model parts. Maintaining consistency during the building phase and ensuring nothing is left to chance provides an element of confidence to the model.

Step 1: Establish the domain – this involves setting the boundaries for the network. It has been established that the model represents dwelling fires as described in section 4.3.1. In part I of the model the network commences with the start of fire at a dwelling and ends at the point of human reaction.

Step 2: Establish the objective – this entails clarifying what results are being sought from the network, in other words the model outputs must be defined. For part I of the model the focus is on human reaction.

Step 3: Establish associated influential themes – here the subject matter which intervenes in the outputs established in step 2 must be clarified. For part I of the model the areas of interest are initial circumstances (*e.g.* time of day, smoke alarm, *etc.*), fire cues and human detection.

Step 4: Brainstorm nodes – this step involves brainstorming all possible parameters that are relevant within the associated themes identified in step 3. All ideas must be listed without judgment. For part I of the model around eighteen nodes were first identified.

Step 5: Select appropriate nodes – following discussion with experts and reviewing of literature the list of nodes from step 4 are reduced to those to be included in the model; nodes with negligible influence are excluded.

Step 6: Connect nodes – using Hugin software (see section 4.3.2), nodes are connected. This entails much experimentation to find the best way to represent the connection between parameters. This also includes linking the different model parts together through transfer / instance nodes.

Step 7: Review network – this involves discussing the structure of the network with experts to ensure there are no missing factors.

Step 8: Obtain data – information is sought from all sources including experts, academic papers, reports, industry articles, and MFRS data base, for each node within the network.

Step 9: Construct probability tables – this involves creating the marginal and conditional probability tables for the nodes. Data has to be combined so as to be represented through probabilities.

Step 10: Test model integrity – here Hugin is used to compile the model and test for conflicts in data by inserting random evidence.

Step 11: Calibrate probabilities – this involves comparing prior probabilities of certain nodes with real world statistics to determine if the model is representative of reality.

4.3.2 Hugin decision support tool

The BN model has been constructed and applied using the fully licensed research edition of the software Hugin Researcher version 7.6 (released February 2012), licensed by Hugin Expert A/S, Denmark. Other software packages were also tested by building and manipulating small networks before a decision was made to go with Hugin. The software is designed for BN modelling and has a series of analysis and decision making tools, as well as facilities for undertaking sensitivity analysis. The programme was selected because of its powerful Graphical User Interface (GUI) which facilitates building, managing, and demonstrating the results of BNs. The GUI is an interactive tool which enables the Hugin Decision Engine (HDE) to be utilized. HDE performs reasoning on a knowledge base represented as a BN, performing all data processing and storage maintenance associated with the reasoning process. Note that during the selection process other software packages were tested and pilot models built

4.3.3 General model description

The BN model was built with three core parts since this assisted in formulating the logic and mapping the sequence of events involved in a dwelling fire; the model also has a fourth part for assessing the response time of emergency services, dealt with in Chapter 7. Having a partitioned model makes it easier to apply and should facilitate any future development. Each part of the model has its own purpose and is useful as a standalone BN, but the parts are also designed to function collectively. The core of the model consists of part I "Initial fire development", part II "Occupant response and further fire development", and part III "Advanced fire situation and consequences". There is a chronological order to the model with part I feeding into part II, which subsequently feeds into part III; note that some part I nodes also connect directly with part III.

Figure 4.7 illustrates with a simple flow chart how the model parts fit together and what they represent. Connections are made between the model parts through transfer nodes which appear both in preceding and succeeding parts of the model. Nodes within the network are mapped sequentially and displayed graphically using a top-down approach in a causal-type relationship. The model commences with the node "Fire start type" in part I, connecting through to part II via the transfer nodes "Human reaction" and "Sprinkler activated", which subsequently connects to part III through the transfer nodes "Fire growth/flashover" and "Fire engines 1 & 2 at scene", finishing in part III with various consequence nodes. Note that certain transfer nodes are also used to demonstrate results and are thus also referred to as output or focus nodes of the model.

Besides the holistic function of the model, each of its parts has a purpose or focal point. Part I is designed to investigate the potential for human reaction given initial fire circumstances; part II focuses on the chance of fire growth/flashover given various actions and events; part III investigates the possible fire outcomes based on fire development and intervention of FRS's. The results are shown through specified output or focus nodes. Section 4.4 onwards presents part I of the model while parts II and III are dealt with in subsequent chapters.

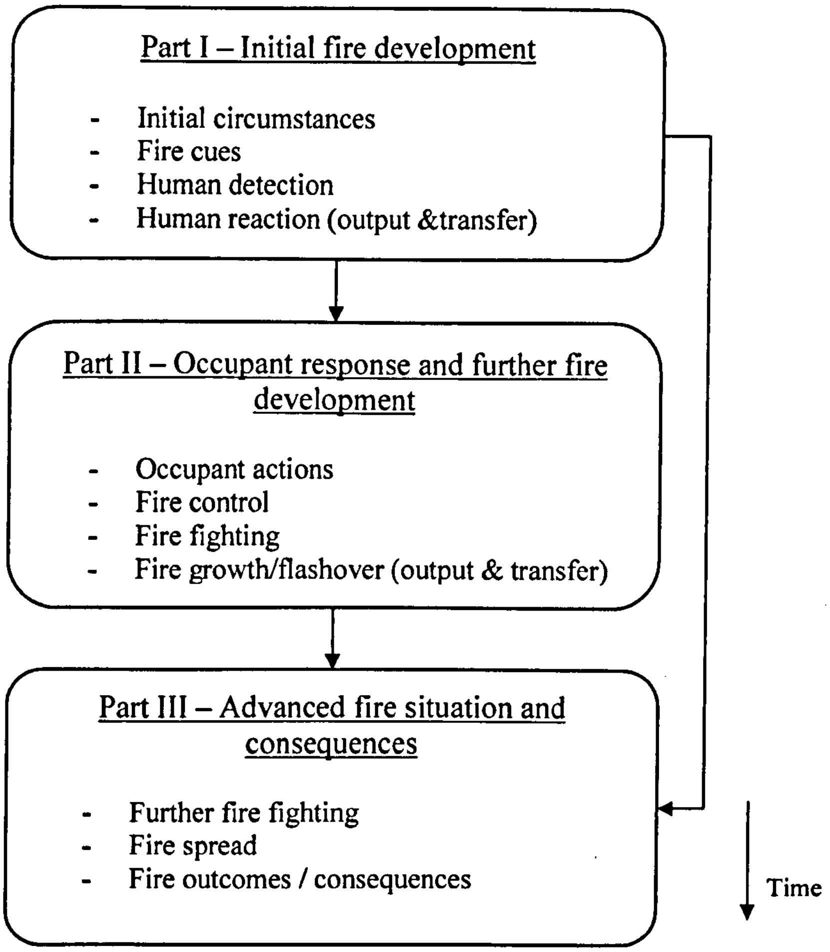


Figure 4.7. Flow chart of events within each part of the BN model.

4.3.3 Assumptions and limitations

There are some underlying assumptions within the model which must be explained in order for the model to be valid and fully understood:

- The model has been built for situations where there is a single occupant, thus it must be assumed that a person is always present within the dwelling. There are three reasons for this: firstly the majority of fires occur when people are within the premises, secondly single occupancy dwellings result in a higher proportion of fatalities, and thirdly the principal aim of FRS's is to prevent fatalities, therefore it makes sense to focus research on situations where there is a risk to life. Further discussion on dwelling occupancy is undertaken in section 2.2.2.1.

- One of the purposes of the model is to be able to calculate the impact of fire on occupant reaction, actions, and ultimately life safety. These factors must occur within a set timeframe in order for them to represent reality. It is not sufficient to simply state that there will be a reaction, for this could happen when the fire is small or large, resulting in very different consequences. The model is designed to investigate events in which human reaction occurs promptly or while the fire is still relatively small. To achieve this, it is necessary to set cut-off points within which events can occur. Thus, the model presented here incorporates various time and space dependent / limited probabilities since it is designed to reflect the fire scenario within a given timeframe or fire size. The importance of time can be appreciated, for example, by looking at the node "Fire appliance 1 and 2 at scene". Here, it is necessary to define a cut-off time within which the node's state could turn positive. If no time limit was set the node would be meaningless as eventually it would turn positive, *i.e.* the FRS would eventually arrive, but by then the dynamics of the fire situation would be completely different. It is important to appreciate that fires develop extremely quickly and events unfold in minutes, sometimes even seconds. In certain circumstances for example, a compartment flashover can occur in as little two minutes from when a fire began. That said, the growth rate between a flaming fire and a smouldering one can be vastly different, and this will reflect in the timing of fire cues. Smoke detection during a flaming fire will typically occur within a couple of minutes from ignition, whereas for a smouldering fire it may take close to an hour (Bukowski *et al.,* 2007). Since part I of the model considers both types of fire, conditional probabilities cannot be time limited since the timing criterion is different. To solve the problem a space or fire size criterion has been used in setting the conditional probabilities. Thus, part I of the model is based on the assumption that fire cues are considered prompt if they occur while the fire is still small, that is, before the fire span reaches 1 metre in diameter viewed on a horizontal-plane. The importance of this limit can be appreciated by examining the node "Smoke in line of sight". If no space limit had been set then the node would become meaningless since eventually it would become positive given the fire continued to grow. There is a section within the next chapter which presents details of the time and space dependencies for parts II and III of the model. The main time or space limits for the model are that part I must develop with the fire being no more than 1 metre in diameter, part II within five minutes from "Human reaction", and part III within twenty minutes of "Human reaction".

- Part I of the model considers only the initial fire situation within the dwelling and does not take into account any external intervention such as actions from passersby. This is because during the initial stages of a fire its small size and limited smoke spread would generally not be detectable from outside the dwelling, thus including a node for "external detection" would add clutter rather than value to the model.
- For smouldering fires, if the fire has not been extinguished within part II of the model, then it must be assumed that it has transformed into a flaming fire.

4.4 PART I OF THE MODEL – INITIAL FIRE DEVELOPMENT

4.4.1 Nodes and structure

Part I of the model (Figure 4.8) is designed to represent the initial fire development *i.e.* the initial circumstances, fire cues, human detection, and human reaction, the latter of which is considered the focus of this part of the investigation. The transfer nodes which feed into part II are "human reaction" and "sprinkler activated". Part I is made up of fourteen chance nodes labelled 1 to 14 each of which has two states except for node 2 which has four states. The nodes are described below by category / group.

Initial circumstances:

1. Fire start type [states: Flaming, Smouldering] – This root node or parentless chance node represents the initiation of the fire which is either flaming or smouldering. Smouldering fires differ from flaming ones in that they produce smoke before visible flames; furthermore the smoke produced by smouldering fires tends to linger well below ceilings and contains relatively large particles. Flaming fires however

develop much faster, releasing more heat and smoke than smouldering fires. Note that the type of fire which develops depends on a series of deterministic and random parameters described in Appendix 1 section A1.1.2. The reason these parameters are not modelled is because there are simply too many, there is little or no data available, and the model would not be improved because of the vagueness in dependencies between them and the type of fire.

2. Smoke alarm installed [states: Yes-ionisation, Yes-optical, Yes-combined, No] – This parentless chance node describes the presence of an automatic smoke alarm; a smoke alarm is a device inbuilt with both a smoke detector and an alarm. There are three types of smoke alarms: ionisation, designed to detect flaming fires faster; optical, designed to detect smouldering fires faster, and; combined. The data for combined smoke alarm also includes those dwellings that have both types of alarm. Note that this node has four states which represent each of the smoke alarm types plus the absence of one.
3. Time of day [states: Day 0700-2259, Night 2300-0659] – This parentless chance node represents the time of day. There are two states set to reflect either a standard day span (0700-2259) for an adult or night span (2300-0659). A night:day ratio of 1:3 has been used based on the recommended eight hours of sleep for an adult.
4. Sprinkler installed [states: Yes, No] – Mirroring node 2, this parentless chance node describes the presence of an automatic heat activated sprinkler system.

Fire cues:

5. Smoke alarm sound [states: Yes, No] – This chance node represents the activation and acoustic propagation of the smoke alarm. Its conditional probabilities are set according to the state of its parent nodes 1 and 2.
6. Fire or smoke visible [states: Yes, No] – This chance node describes the situation where fire and/or smoke are visible by a person before the fire reaches 1 metre in diameter. This situation will likely be limited to the fire occurring within the same room as the dwelling occupant or within an adjacent room/corridor with open doors through which either a flickering of flames or spreading of smoke may be visible. A

flaming fire will emit large noticeable flames and a great deal of smoke; a smouldering fire will have no flames and a lower rate of smoke production. Even though a smouldering fire may burn for longer, it is still less likely to be noticed. The conditional probabilities are set in relation to its single parent node 1.

7. Extensive smoke spread [states: Yes, No] – This chance node represents the extent of smoke spread throughout the dwelling. If smoke has spread from the room of origin whilst the fire is still smaller than 1 metre in diameter then smoke spread can be considered extensive. Conditional probabilities are set in relation to the state of its sole parent node 1.
8. Sprinkler activated [states: Yes, No] – This chance node represents the activation of the automatic heat triggered sprinkler system which entails water being sprayed throughout the dwelling. The conditional probabilities are set according to the state of its parent nodes 1 and 4.

Human detection:

9. Human awake [states: Yes, No] – This chance node describes the human condition of either being awake or asleep. The state of this node is affected by its single parent node 3 "Time of day".
10. Human detection SOUND [states: Yes, No] – This chance node represents a human detecting the fire by hearing the smoke alarm. The conditional probabilities of this node are set in relation to its parent nodes 1, 5 and 9. A human may also detect the fire through other noises such as crackling, shuffling, and breaking of materials during combustion; since this is not represented through a separate node, a Leaky Noisy-OR gate is used in formulating the CPT. The leak probability depends on the type of fire, reason for which node 1 is a parent of "Human detection SOUND".
11. Human detection VISUAL [states: Yes, No] – This chance node represents a human detecting the fire by seeing fire or smoke. The conditional probabilities are set in relation to its parent nodes 6 and 9.
12. Human detection SMELL [states: Yes, No] – This chance node represents a human detecting the fire by smelling smoke. The conditional probabilities are set in relation

to its parent nodes 7 and 9. Note that node 9 "Human awake" is included as a cause of "Human detection SMELL" based on the assumption that a person who is awake will also be mobile thus there is a chance he/she could move to a location where the fire could be smelt, even though there has not been extensive smoke spread.

13. Human detection WET [states: Yes, No] – This chance node represents a human detecting the fire by feeling the water from the sprinkler system. The conditional probabilities are set in relation to the parent nodes 8 and 9.

Outputs:

14. Human reaction [states: Yes, No] – This chance node describes a human understanding the significance of a fire situation and reacting rationally. The assumption is once a human is alerted (either through sight, sound, smell, or touch), the chances of reacting are the same regardless of the method. The reasoning behind a human not reacting is based on the possibility that he/she may be mentally or physically handicapped, thus they may not understand how to respond or may not be able to physically carry out any action. In putting together the CPT data the following exceptions had to be considered:
    - Some mentally handicapped people have received specialist training on how to react in emergency situations.
    - Some physically handicapped people might have someone with them at the time of the incident or may have an emergency call device to hand.

    The conditional probabilities of this node are set in relation to its parent nodes 10, 11, 12, and 13. Note that these probabilities do not vary with the number of parent nodes that have positive states, that is, one positive detection results in the same probability of human reaction as would two, three, or four simultaneous detections. Human reaction is the focus node for part I of the BN model; the node is also one of the inputs or links into part II of the model, in other words it is a transfer node.

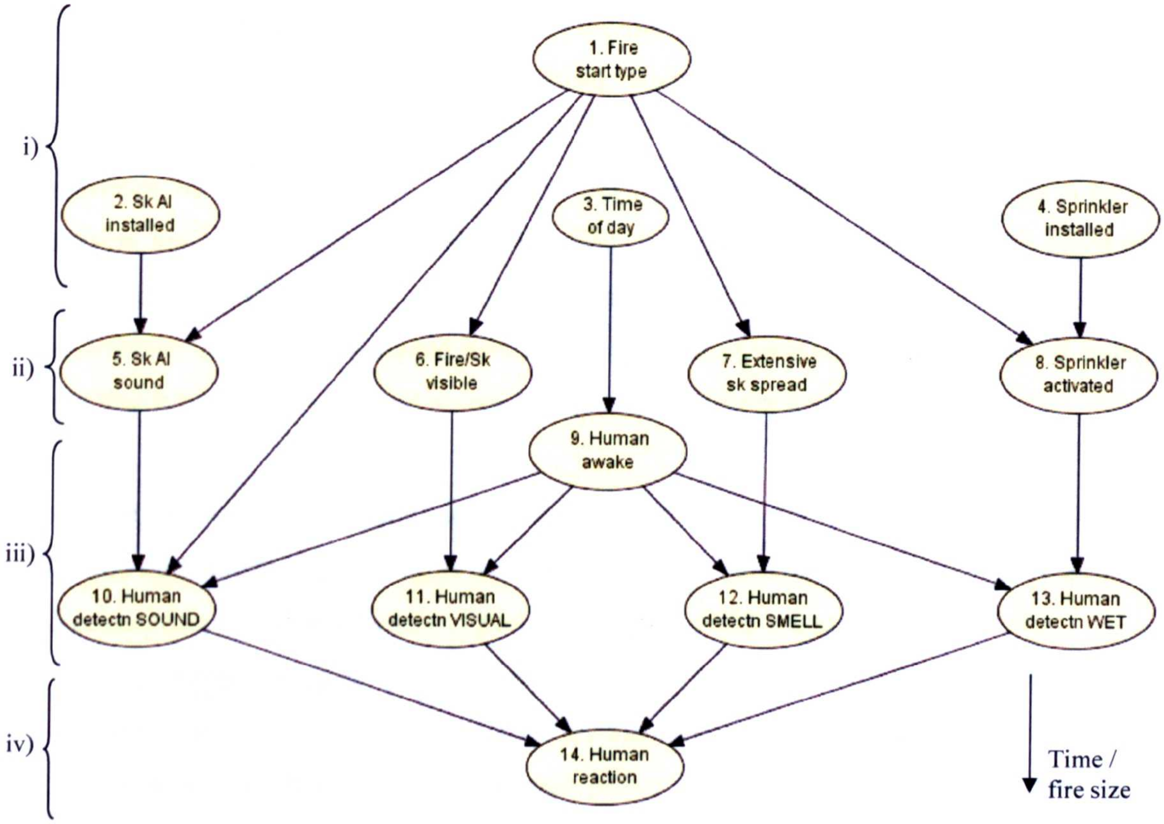


Figure 4.8. BN model Part I representing initial fire development. Nodes are grouped into: i) Initial circumstances; ii) Fire cues; iii) Human detection; iv) Human reaction

Nodes in part I of the network have been laid out chronologically from top to bottom (Figure 4.8). Events which can occur at roughly the same moment or that are similar have been positioned along the same horizontal line where possible; for example, the four fire cues (nodes 5 to 8), can be seen lined up horizontally. It is worth noting that root nodes generally form part of the existing circumstances during the fire, while chance nodes represent the events which could occur during its development.

4.4.2 Causation and node connections

As previously mentioned nodes throughout the network are connected via parent-child type relationships. This relationship can be causal, where the parent directly is a cause of the child node, or it can be an association, where the parent node is correlated with the occurrence of the child node. Generally networks arranged with respect to time and causation are known as causal BNs. That said, it is difficult for researchers to agree on a definition of causality, as pointed out in chapter 10 of Neapolitan's book on learning (2004). Nevertheless, the model presented here can be thought of as a causal BN, though it must be noted that it has both causal and associated/correlated parent nodes.

There are various ways parent nodes collectively determine the state of child nodes, based in principle on Boolean logic. Within the model there are variations in the type of relationship and connecting gate between sets of parents and their children, as outlined below:

- The Noisy-OR gate. In this type of connection at least one of the parent nodes X_i must be in a positive state in order for the child node Y to have a chance p_i of being in a positive state; furthermore each parent node alone is sufficient to result in the child node. There are three slightly different situations to which the Noisy-OR gate is applied in this model. In situation one (Table 4.1a) any combination of positive parent nodes can result in a positive child node with each combination potentially resulting in a different probability p_i. In situation two (Table 4.1b), once one of the parent nodes becomes positive the state of all other parents becomes irrelevant to the state of the child node; the probability of the child node is the same under all parent nodes. In situation three (Table 4.1c) the child node has at least one causal parent and at least one non-causal parent the latter of which can be referred to as being correlated or associated with the child node, effectively acting as a 'conditional modifier'. Here the non-causal parent node can only influence the child node if the causal parent node is in a positive state.

Tables 4.1a-c. Truth tables for Noisy-OR gate variations: situation one left (4.1a), situation two centre (4.1b), and situation three right (4.1c).

Parent		Child
X_1	X_2	Y
0	0	0
1	0	$1 \times p_1$
0	1	$1 \times p_2$
1	1	$1 \times p_{(1,2)}$

Parent		Child
X_1	X_2	Y
0	0	0
1	0	$1 \times p_i$
0	1	$1 \times p_i$
1	1	$1 \times p_i$

Parent		Child
X_1	X_2	Y
0	0	0
1	0	$1 \times p_1$
0	1	0
1	1	$1 \times p_{(1,2)}$

An example of situation one is contained in part I of the model connecting parent nodes "Extensive smoke spread" and "Human awake" with the child node "Human detection SMELL". Situation two can be found in the connection of the four Human detection nodes with their child node "Human reaction". Finally an example of situation three can be seen connecting the parent nodes "Sprinkler activated" and "Human awake", and child node "Human detection WET".

- <u>The Leaky Noisy-OR gate</u>. This gate is similar to the Noisy-OR gate except for the fact that the child node can still be positive even if all the parent nodes are negative (Henrion 1989). Leaky Noisy-OR is applicable to situations where the child node can still occur through other factors or causes not accounted for within the parent nodes (Table 4.2); this missing information is covered within the conditional probability data. The leak probability p_o is expressed in equation (4.6) with y representing the child node and x'_n the parent nodes in a negative state:

$$p_o = P(y|\, x'_1, x'_2, \dots, x'_n) \tag{4.6}$$

An example of a Leaky Noisy-OR gate can be found between the child node "Human detection SOUND" and its parent nodes "Smoke alarm sound", "Human awake", and "Fire start type". Here the child node may still be true regardless of the state of all the parent nodes. This is because a human can detect fire through other sounds such as crackling, breaking and shuffling of materials during combustion.

Note that the node "Fire start type" is included as a parent to affect the probability of leak given that the intensity of noise generated from flaming fires is superior to that from smouldering fires.

Table 4.2. Truth table for Leaky Noisy-OR.

Parent		Child
X_1	X_2	Y
0	0	$1 \times p_0$
1	0	$1 \times p_1$
0	1	$1 \times p_2$
1	1	$1 \times p_{(1,2)}$

- The Noisy-AND gate. In this gate all the parent nodes must be in a positive state for the child node to have a chance of being in a positive state (Table 4.3). Essentially only the conjunctive effect of the parent nodes is possible, that is:

$$P(Y| X_1, X_2) = \{1 \text{ if } X_1 = x_1 \text{ and } X_2 = x_2, \text{ else } 0\} \tag{4.7}$$

An example of this gate can be found in part I of the model connecting the parent nodes "Fire/smoke in line of sight" and "Human awake" with the child node "Human detection VISUAL".

Table 4.3. Truth table for Noisy-AND.

Parent		Child
X_1	X_2	Y
0	0	0
1	0	0
0	1	0
1	1	$1 \times p_{(1,2)}$

The type of relationship between parent and child nodes is not shown in the DAG, but rather is embedded within the conditional probability data. For example the node "Human detection VISUAL" is related to its parent nodes through a Noisy-AND connection; thus the CPT for this node shows it can only be true if both its parents are true (see Table 4.4).

Table 4.4. CPT for Human detection VISUAL

Fire/Sk visible		Y		N	
Human awake		Y	N	Y	N
Human detection VISUAL	Y	0.97	0	0	0
	N	0.03	1	1	1

4.4.3 Model d-separation and Markov blanket

D-separation and Markov blanket have been defined in section 4.2.5. The focus node for part I of the model is "Human reaction". To demonstrate that the model has been simplified and that there are no superfluous nodes, a d-separation test has been undertaken using Hugin. Figure 4.9a shows d-separation in which the focus node is highlighted, the nodes which are *d-separated* (relevant to it) have a tick, and those which are *d-connected* (irrelevant to it) have a cross, in this case none. Additional d-separation checks have been conducted based around other central nodes to ensure network relevance of respective influencing nodes. Figure 4.9b provides the Markov blanket for the focus node, portrayed by nodes with a cross through them. If evidence is inserted into any of these nodes the focus node becomes conditionally independent of the rest of the network. The diagram is shown out of interest only since further network inspection is not required here.

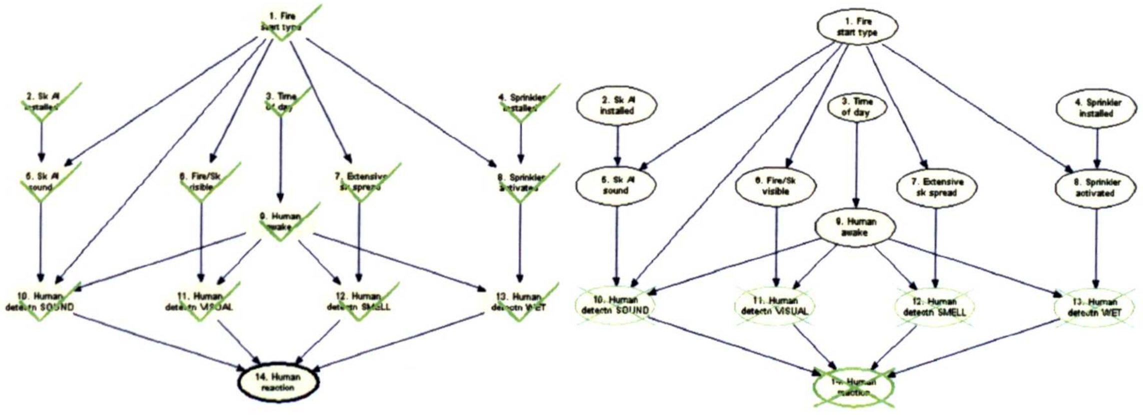


Figure 4.9a-b. BN model Part I showing d-separation (left) and Markov blanket (right).

4.4.4 Axioms

A system of knowledge such as the BN model presented in this chapter can be used to make a series of assertions. These assertions are essentially based upon a set of small understandable sentences, or axioms, embedded within the model. If a system is to provide reliable results it must first be shown to work rationally. Thus, in order to verify the reasoning behind the BN model, a set of axioms are presented and individually tested. These axioms have been formulated to represent different aspects of interaction of the nodes within the model and their degree of influence upon a node of interest. For example, one axiom tests how the number of parent nodes in a positive state affects a relevant child node; another axiom tests how the distance between influencing nodes affects a selected node of interest.

In the statements below, reference is made to the input nodes 1, 2, 3 and 4 which represent respectively "Fire start type", "Smoke alarm installed", "Time of day", and "Sprinkler installed". The focus node 14 "Human reaction" is also included in some of the axioms; all nodes are described in section 4.4.1. Reference is also made to groups of nodes; these groups are shown in Figure 4.8. For the axioms below the following applies:

N denotes any node from 1 to 13.
F denotes the focus node 14.

I denotes an input node (node numbers 1 to 4).

$u = [1, ..., n]$ and $v = [1, ..., n]$ identify node numbers

p and q identify number of nodes

Axiom 1: A change in the probabilities of any node will influence the probability of the focus node and vice versa.

$$dP(N) \leftrightarrow dP(F) \qquad (4.8)$$

Axiom 2: Nodes which are closer to the focus node will have a greater influence on it compared to those which are further away; individual exceptions however can apply. For part I of the model changes to nodes in *group i* (nodes 1 to 4) will generally have a smaller effect on the focus node, compared to changes made in *group iii* (nodes 9 to 13).

$$P(N_{u=[1, ..., 4]}) \propto k_{u=[1, ..., 4]} P(F) \text{ and } P(N_{v=[9, ..., 13]}) \propto c_{v=[9, ..., 13]} P(F) \qquad (4.9)$$

where the constants of proportionality k and c belong to $R=(0,1)$ and $k < c$

Axiom 3: The more nodes featuring a posterior increase in probability, the greater the posterior probability increase for the focus node.

For p number of nodes each of which has a probability change (i.e. each $dP(N) = x$), then $P(F) = P_1$

For q number of nodes each of which has a probability change (i.e. each $dP(N) = x$), then $P(F) = P_2$

$$\text{If } p \in q, \text{ then } P_1 < P_2 \qquad (4.10)$$

Axiom 4: The input nodes are independent of each other and therefore a change in one will not affect the others.

I_u and I_v represent Input nodes u and v where ($u=1, 2, 3,$ or 4) and ($v=1, 2, 3,$ or 4)

$$I_u \perp I_v, \quad u \neq v \qquad (4.11)$$

The four axioms above have been tested in section 4.6 in order to validate part I of the BN model.

4.5 DATA FOR THE BN MODEL

It is important to stress at this stage that the numerical results of the model are not significant in an absolute sense but rather serve to demonstrate the practicability of the model. Once fed with a full set of verified data the model results should improve confidence within planning and decision making under uncertainty.

Data for part I of the model has been compiled from a variety of sources and is by no means completely representative of each variable. Problems encountered include data being scarce, non-existent, based on small samples, old, and representative of other geographical regions. Appendix 6 provides the marginal and prior conditional probability distributions for all 14 nodes. As mentioned above, the purpose of this part of the thesis is to provide a valuable model to represent fire scenarios in a dwelling. Work on improving deficiencies in data can be dealt with in subsequent research. Information and data fed into the model through marginal and conditional probabilities has originated primarily from Communities and Local Government, Merseyside Fire and Rescue Service, academic papers, books, and expert opinion. Data used is both objective and subjective.

Completing CPTs requires data and/or knowledge about the relevant node. For certain nodes there is little or no available data. Within part I of the model, this is for example true for human detection in response to fire cues, as pointed out in a study on recognition of fire cues by Bruck and Brennan (2001). For cases where there is a lack of hard data CPTs must be completed through subjective reasoning or the application of expert judgement. This process can be briefly demonstrated by looking at the node “Human detection SMELL” which represents the chance of a human detecting fire by smelling smoke; the parent nodes are “Extensive smoke spread” and “Human awake”. In order to put together a meaningful estimate, experts would have to judge the situation and provide their opinion; this exercise may be quantitative or qualitative depending on the method formulated. In putting together an estimate, an expert would have to consider one parent node at a time. Taking the parent node “Extensive smoke spread” as an example, the expert might begin by identifying all the reasons why a human would not smell the smoke, given extensive smoke spread. In this case the reasons could be open windows, air currents taking the smoke away from the occupant, an illness such as a cold, a medical condition such as anosmia (having no sense of smell), or severe drug / alcohol intoxication. Then subjective judgements would have to be made on the probability of fulfilment of each of these reasons; these probabilities would then have to be combined into one figure. The process would have to be repeated with several experts and the individual estimates compound into one. In bringing together all the expert opinions, weightings might be applied for example as a function of the expert's experience or current involvement in the subject; this process will also be applied in subsequent chapters. It must be noted that where hard data was unavailable to input into the model, subjective estimates were applied by the author based on personal communication with experts, and from reviewing academic and industrial information. Table 4.5 summarizes the origins of data for each node of part I the model. There were many sources of literature but it is not practical to list them all in the table. For example node 3 was compiled from Siegel (*n.d.*) and Sukegawa *et al.* (2009), whilst node 7 from Yung (2008), Furness and Muckett (2007), and Stollard and Abrahams (1999). Table 4.5 also provides the number of states, parent nodes, and permutations for each node to give an idea of how far data had to be broken down before being inserted into each corresponding probability table within the network.

There is a subjective element within the data for most nodes as indicated in Table 4.5, though it must be noted that the 'degree of subjectivity' varies from case to case. Node 3 "Time of day" for example contains relatively little subjectivity. In this case research indicates that adults generally sleep between 6 to 9 hours per night, with young adults averaging 8 hours (Siegel, *n.d.*). Other studies vary slightly, for example Sukegawa *et al.* (2009) indicate that adults usually sleep 7 hours per night. Since this node is one of the least influential within the model an approximate figure was all that was required, thus it was decided that 8 hours or 1/3 of a day would be used as the figure indicating night or typical human sleep time. Another example of a node with a low degree of subjectivity is "Human awake" which is based on information provided by Schur (1994) (cited in Night Owl Network 2010). Schur (1994) states that according to most research the percentage of humans awake at night is 20%, though the text also points out that one leading researcher has the figure at 10%; Schur proceeds to challenge these figures indicating that it should be nearer 40%. In the BN a judgement was made to adopt the figure of 20% because it is supported by the majority of relevant research; this judgement is what ultimately gives the data within the node its low degree of subjectivity. Conversely, data for node 4 "Sprinkler installed" has a high degree of subjectivity. Since no published data exists, information was elicited from two experts involved in the residential fire sprinkler industry and one FRS officer. The first expert, the Secretary General of The British Automatic Fire Sprinkler Association (BAFSA), pointed out that less than 2% of dwellings have sprinklers installed (P.C., tel., Dec 2010). Another expert, a consultant at Domestic Sprinklers PLC., put the figure at around 1% (P.C., email, Dec 2010), while the experienced FRS officer estimated it to be 1.5% (P.C., interview, Nov 2010). Since at this stage of research the objective was to produce a functional BN model nothing more was done with this data and the mean value of 1.5% was inserted into the node.

Table 4.5. Probability table details for each node and origins of data.

Node	Node name	# of states	# of parent nodes	# of permutations in prob. table	Probabilities compiled from	Subjective element
1	Fire start type	2	0	2	Expert opinion, literature	Yes
2	Smoke alarm installed	4	0	4	C&LG*	No
3	Time of day	2	0	2	Literature	Yes
4	Sprinkler installed	2	0	2	Expert opinion	Yes
5	Smoke alarm sound	2	2	16	C&LG, expert opinion	Yes
6	Fire / smoke visible	2	1	4	Expert opinion, literature	Yes
7	Extensive smoke spread	2	1	4	Expert opinion, literature	Yes
8	Sprinkler activated	2	2	4	Literature	Yes
9	Human awake	2	1	4	Literature	No
10	Human detection SOUND	2	3	4	Expert opinion, literature	Yes
11	Human detection VISUAL	2	2	4	Expert opinion, literature	Yes
12	Human detection SMELL	2	2	4	Expert opinion, literature	Yes
13	Human detection WET	2	2	4	Expert opinion, literature	Yes
14	Human reaction	2	4	32	Expert opinion, literature	Yes

* Communities and Local Government (C&LG)

Gathering information from fire incidents is important both for inputting data into the model and for validating results. The model should collectively help assess the success of different fire fighting measures, the effectiveness of certain actions, and the likelihood of consequences. It is important however, to bear in mind that the model outputs can only be as good as the inputs. Part of the inputs into the model will come from data collected at major or medium fire incidents (fires greater than one metre in diameter). The problem lies in that major/medium fire incidents are few and far between meaning that data sets are often too short to undertake any significant statistical analysis. This issue is further accentuated because time varies the boundaries and benchmarks of the world we live in. Demographics, industrial activities, fire prevention activities, mitigating measures, fire and rescue approaches, all change with time. This means that incident data becomes less representative of reality the older it gets. If dated information cannot be used within the same context as recent data, then the upshot is shorter data sets. This problem is enhanced by the fact that there are many different types of fires and thus incident data must be categorized for statistical analysis. If data sets for major/medium fire incidents are too small then a solution might be to consider more frequently occurring minor incidents or even near misses. Data from these smaller incidents could be extrapolated to represent those of major incidents.

There are various studies relating the frequency of minor incidents to those of major accident events. Heinrich (1950) (cited in Kristiansen, 2005) suggested that there are 300 no-injury incidents for every major accident (Figure 4.10a), while (Bird, 1969) proposed the ratio to be 600 no-injury incidents for every major injury (Figure 4.10b). In other work, Ferguson *et al.* (1999) (cited in Kristiansen, 2005) postulated that there are 1000 incidents and 1000 situations where safety is compromised for every accident. There are other studies, but the point to remember is that each is geared to different circumstances and activities. Furthermore, each author has a different definition for a major accident, minor accident, or near miss. Thus any such linking of minor incidents to major incidents would have to be done within a fire and rescue context rather than a universal one. There are however some issues with linking minor to major incidents within fire and rescue. One common problem with minor incidents is that data is often not recorded because the incident is neutralized before there is time to summon the emergency services. Moreover such incidents frequently go unreported because there is no insurance cover in place or because the cost of damage is less than the insurance premium. As for near misses, these are usually only reported in workplaces or public buildings, but rarely in dwellings. These inconsistencies mean that caution must be exercised in extrapolating minor incident data to represent major incidents.

Figure 4.10 a-b. Accident pyramids from Heinrich (1950) (left) and Bird (1969) (right) hypothesising major to minor accident ratios.

4.6 MODEL VALIDATION

Prior to generating results for part I of the BN model a series of tests were carried out to demonstrate that the network was working as intended. The exercise involved testing the four axioms presented in section 4.4.4 which embody some of the underlying logic within the model. Marginal and conditional probability data have been inserted into the model, and is discussed in section 4.5. Based on this data, the probability that there is "Human reaction" during a dwelling fire prior to external intervention is 79.04%. To test the axioms the probabilities of some nodes were varied and the effect upon other nodes noted. The results are provided below ordered according to the axiom tested.

Axioms 1 and 2

The probabilities of nodes 1 to 13 were individually varied in order to examine the effect upon the focus node "Human reaction". For each node the probability of its first state was increased by an absolute value of 5% and hence the probability of its other state lowered by 5%; for example the probability of node 1 [state: flaming] was increased from 70% to 75% whilst [state: smouldering] was lowered from 30% to 25%. In the case of node 2 where there are four states, the other three states were decreased proportionally. The effect upon the likelihood of successful "Human reaction" was recorded. Figure 4.11 presents the results using a bar to display the individual effect of each node upon the focus node. The bar chart confirms the validity of the following axioms:

- Axiom 1 – Changes in the probabilities of any node will affect the probability of "Human reaction".
- Axiom 2 – In general, nodes which are closer to the focus node will have a greater influence on it compared to those which are further away. Group *i* nodes (1 to 4 denoted by blue bars) have a smaller influence on "Human reaction" than group *iii* nodes (9 to 13 denoted by orange bars). A trend line has been added to highlight this further.

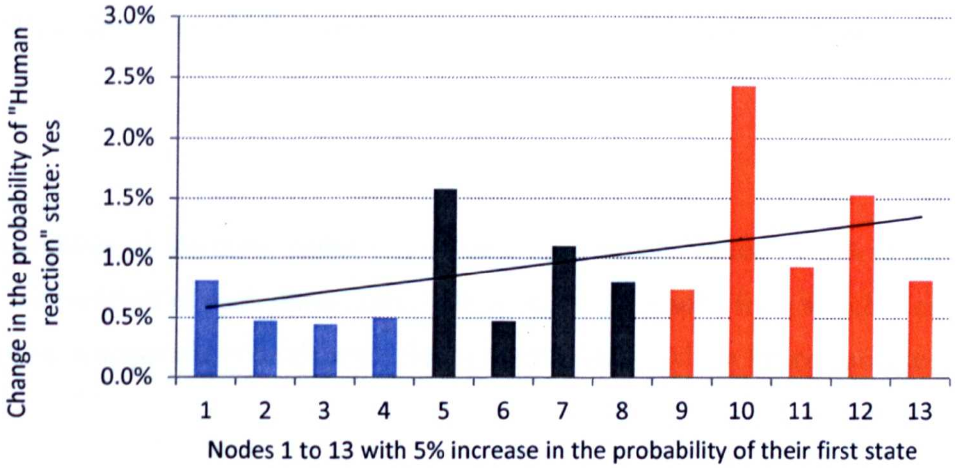


Figure 4.11. Bar chart showing how individual changes in nodes 1 to 13 affect the focus node "Human reaction".

Axiom 3

To corroborate this axiom the probabilities of nodes 5 to 8 were increased by 5% and the effect upon the focus node recorded. The node increments were carried out one at a time but the effect upon the focus node aggregated. This was achieved by locking the probability of each node once it had been increased by 5%. The results are shown in Figure 4.12; it is clear that raising the probability of a greater number of nodes increases further the probability of the focus node, thus confirming this axiom.

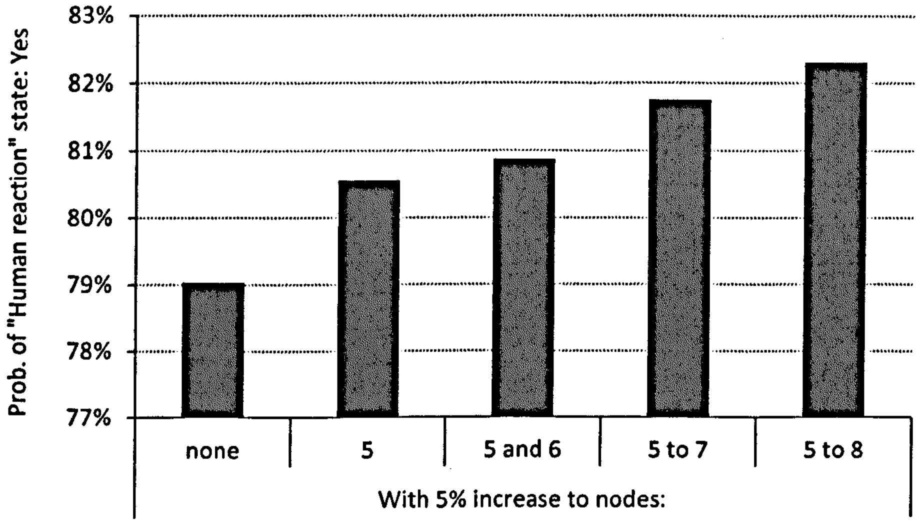


Figure 4.12. Bar chart of "Human reaction" state: Yes, under different node probabilities.

Axiom 4

The probabilities of the input nodes 1 to 4 were individually varied by 5% to determine if they are independent of each other. Table 4.6 provides the results from which it can be seen that changes to a specific node do not affect the other nodes, which hence validates axiom 4.

Table 4.6. Table showing changes to the probability of the first state of each input node and its effect on other input nodes

5% change made to:	*Effect on:*			
	Node 1	*Node 2*	*Node 3*	*Node 4*
No node	70.00%	60.00%	66.70%	1.50%
Node 1	n/a	60.00%	66.70%	1.50%
Node 2	70.00%	n/a	66.70%	1.50%
Node 3	70.00%	60.00%	n/a	1.50%
Node 4	70.00%	60.00%	66.70%	n/a

4.7 MODEL PART I CASE STUDIES

4.7.1 Four case studies

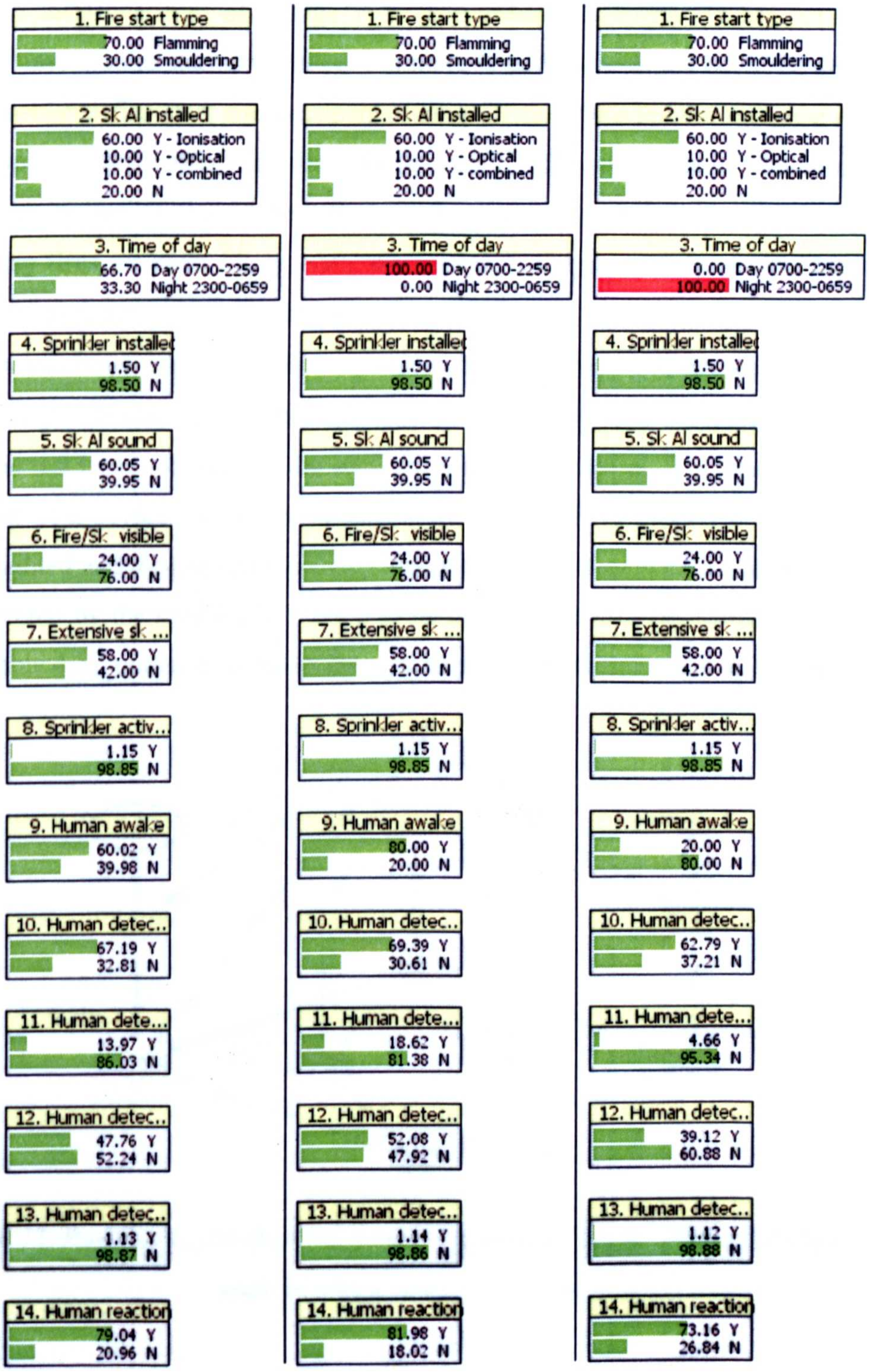
Part I of the model has been used to study a series of possible real world scenarios. In each of the cases all variables remain unchanged except for those directly involved in the study. Posterior probability distributions are computed for likelihood diagnosis of nodes of interest given particular evidence. The focus of part I of the model is on human reaction to dwelling fires and the various situations in which this may arise, for example, the time of day when it occurs, the type of fire which develops, the presence of fire detection devices, *etc*. The case studies presented have been chosen around such variables to demonstrate how they can influence the probability of human reaction; they are intended to show how the model can be used in practice to address some common concerns regarding dwelling fires. Four case studies are now presented:

Case 1 – Daytime fire versus nighttime fire

Most fires occur during the day however nighttime fires proportionally result in more casualties (Bruck and Brennan, 2001). The reason is primarily due to humans being asleep which lowers the ability to respond to fire cues; sleep as a risk factor in fire is discussed by Bruck (2001) who assesses the auditory arousal of a person at a bedside during a fire. Delays in awakening mean that the fire will generally be larger and more potent by the time a human has awoken. Furthermore, the fact that a human is stationary while asleep rather than mobile as during the day eliminates the chance of simply stumbling upon the situation. Other reasons for night fires being more deadly can include upper floor bedroom locations and the fact that there may be more people present in the dwelling. Part I of the model is about human detection/reaction therefore these other reasons affecting escape and rescue are not represented here.

Test 1.1: The objective of this case study is to analyse the significance of a nighttime fire versus a daytime one in terms of human detection and reaction. The results are provided in Table 4.7. Since this is the first case study all the nodes of part I of the model are shown in Table 4.7 to provide the reader with a complete view of the marginal and conditional probabilities before evidence was inserted (left column). Once evidence was entered for "Time of day" posterior probabilities were computed for nodes 9 to 14 (middle and right columns of Table 4.7). Nodes with evidence inserted are portrayed by having red bars while probabilities by green bars. As would be expected human detection and reaction were higher during the day. The results however do shed an insight into the fact that a human's ability to detect fire through sight (node11) and smell (node 12) drops considerably during the night, particularly when compared to human detection through sound (node 10). This point highlights further the importance of having an audible fire alarm within dwellings.

Table 4.7. Table of results showing the effect of "Time of day" on human detection and reaction. (To identify nodes whose names are not fully visible and for a node description, refer to section 4.4.1).



1. Fire start type	**1. Fire start type**	**1. Fire start type**
70.00 Flamming	70.00 Flamming	70.00 Flamming
30.00 Smouldering	30.00 Smouldering	30.00 Smouldering
2. Sk Al installed	**2. Sk Al installed**	**2. Sk Al installed**
60.00 Y - Ionisation	60.00 Y - Ionisation	60.00 Y - Ionisation
10.00 Y - Optical	10.00 Y - Optical	10.00 Y - Optical
10.00 Y - combined	10.00 Y - combined	10.00 Y - combined
20.00 N	20.00 N	20.00 N
3. Time of day	**3. Time of day**	**3. Time of day**
66.70 Day 0700-2259	100.00 Day 0700-2259	0.00 Day 0700-2259
33.30 Night 2300-0659	0.00 Night 2300-0659	100.00 Night 2300-0659
4. Sprinkler installe	**4. Sprinkler installe**	**4. Sprinkler installe**
1.50 Y	1.50 Y	1.50 Y
98.50 N	98.50 N	98.50 N
5. Sk Al sound	**5. Sk Al sound**	**5. Sk Al sound**
60.05 Y	60.05 Y	60.05 Y
39.95 N	39.95 N	39.95 N
6. Fire/Sk visible	**6. Fire/Sk visible**	**6. Fire/Sk visible**
24.00 Y	24.00 Y	24.00 Y
76.00 N	76.00 N	76.00 N
7. Extensive sk ...	**7. Extensive sk ...**	**7. Extensive sk ...**
58.00 Y	58.00 Y	58.00 Y
42.00 N	42.00 N	42.00 N
8. Sprinkler activ...	**8. Sprinkler activ...**	**8. Sprinkler activ...**
1.15 Y	1.15 Y	1.15 Y
98.85 N	98.85 N	98.85 N
9. Human awake	**9. Human awake**	**9. Human awake**
60.02 Y	80.00 Y	20.00 Y
39.98 N	20.00 N	80.00 N
10. Human detec...	**10. Human detec...**	**10. Human detec...**
67.19 Y	69.39 Y	62.79 Y
32.81 N	30.61 N	37.21 N
11. Human dete...	**11. Human dete...**	**11. Human dete...**
13.97 Y	18.62 Y	4.66 Y
86.03 N	81.38 N	95.34 N
12. Human detec...	**12. Human detec...**	**12. Human detec...**
47.76 Y	52.08 Y	39.12 Y
52.24 N	47.92 N	60.88 N
13. Human detec...	**13. Human detec...**	**13. Human detec...**
1.13 Y	1.14 Y	1.12 Y
98.87 N	98.86 N	98.88 N
14. Human reaction	**14. Human reaction**	**14. Human reaction**
79.04 Y	81.98 Y	73.16 Y
20.96 N	18.02 N	26.84 N

Case 2 – Types of smoke alarms and their absence within dwellings

Smoke alarms are the primary fire safety device recommended and installed in dwellings. Fire safety campaigns have both improved the public's awareness of their importance and assisted in installing free of charge a large number of alarms. Today the majority of dwellings have smoke alarms installed, but there is still more which could be done to lower the time between fire start and occupants being alerted. One known measure is to ensure that the type of smoke alarm installed matches the likelihood of type of fire, in other words installing an ionization alarm where flaming fires are most likely and an optical one where smouldering fires are most likely; naturally having both types of alarm would be ideal but this would implicate greater investment. Thus, the model has been used to emphasize the importance of choice when installing a particular type of smoke alarm; this could serve, for example, as justification for adapting Home Fire Safety Check campaigns undertaken by FRS's. The test involved running the scenario for different types of smoke alarms including the absence of a device. Before commencing node 2 in which evidence was to be inserted was highlighted and *d-separation* shown (Figure 4.13). This allowed the nodes which would not be affected by the changes to node 2 to be crossed-out and subsequently left out of the results (Table 4.8); nodes included in the results are marked with a tick in Figure 4.13.

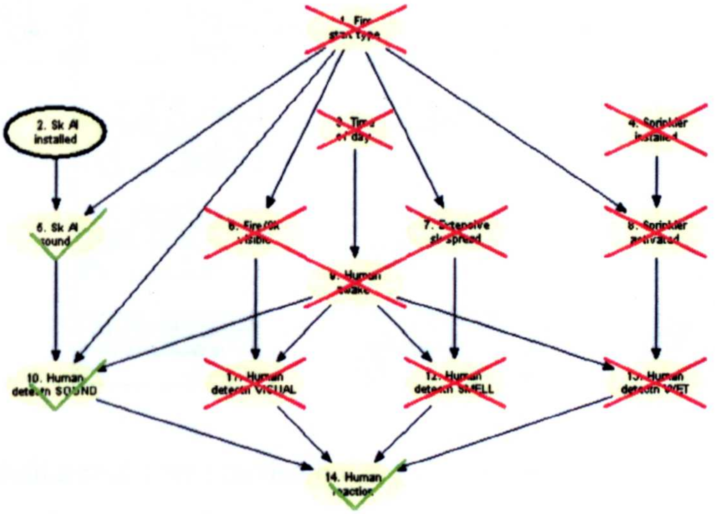
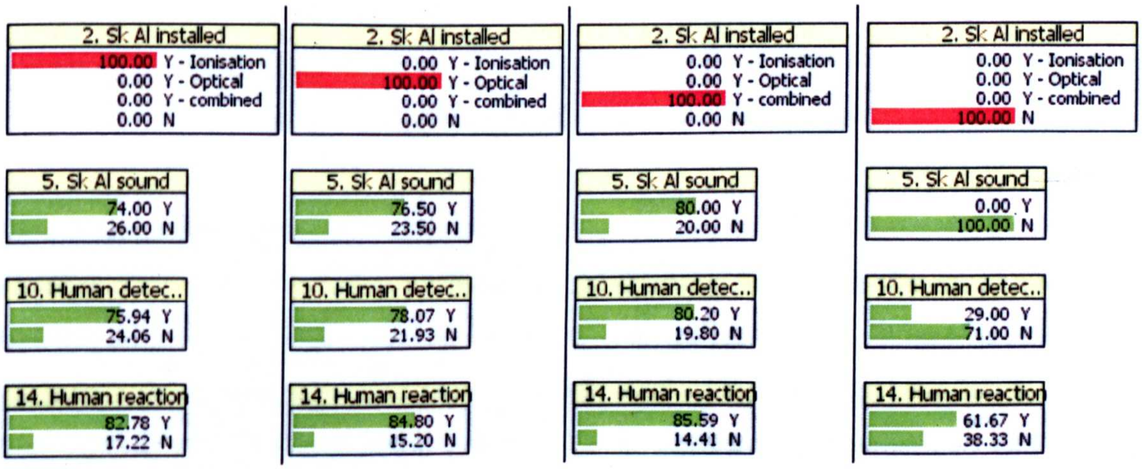


Figure 4.13. Part I of model showing d-separation with "Smoke alarm installed" as the node in which evidence is entered.

Test 2.1: With the marginal probability for "Fire start type" fixed (70% flaming, 30% smouldering) the presence or absence of different types of smoke alarms were analysed for their effect upon node 10 "Human detection SOUND" and node 14 "Human reaction". Evidence was inserted into node 2 "Smoke alarm installed" portrayed by the red bars below in Table 4.8; posterior probabilities are depicted by the green bars in the rest of the nodes. The results show that the type of smoke alarm installed does not have a significant effect on either "Human detection SOUND" or "Human reaction". The maximum differences between the combined and ionisation alarms are 4.3% for node 10 and 2.8% for node 14; however the absence of an alarm lowers considerably the percentage of humans that would react promptly in the event of a fire (*circa.* 51% for node 10 and *circa* 24% for node 14). This indeed is common knowledge, but what is not so clear is how the type of smoke alarm combines with the time of day to affect human detection; this is examined in test 2.2.

Table 4.8. Table of results showing the effect of "Smoke alarm installed" on human detection and reaction. (To identify nodes whose names are not fully visible and for a node description, refer to section 4.4.1).



2. Sk Al installed	2. Sk Al installed	2. Sk Al installed	2. Sk Al installed
100.00 Y - Ionisation 0.00 Y - Optical 0.00 Y - combined 0.00 N	0.00 Y - Ionisation 100.00 Y - Optical 0.00 Y - combined 0.00 N	0.00 Y - Ionisation 0.00 Y - Optical 100.00 Y - combined 0.00 N	0.00 Y - Ionisation 0.00 Y - Optical 0.00 Y - combined 100.00 N
5. Sk Al sound	5. Sk Al sound	5. Sk Al sound	5. Sk Al sound
74.00 Y 26.00 N	76.50 Y 23.50 N	80.00 Y 20.00 N	0.00 Y 100.00 N
10. Human detec..	10. Human detec..	10. Human detec..	10. Human detec..
75.94 Y 24.06 N	78.07 Y 21.93 N	80.20 Y 19.80 N	29.00 Y 71.00 N
14. Human reaction	14. Human reaction	14. Human reaction	14. Human reaction
82.78 Y 17.22 N	84.80 Y 15.20 N	85.59 Y 14.41 N	61.67 Y 38.33 N

Test 2.2: A test similar to 2.1 was carried but this time node 3 "Time of day" was set to day and subsequently night. Since node 3 also influences "Human reaction" through other paths, the sole effect of "Smoke alarm installed" had to be examined only through "Human detection SOUND". The results (Figure 4.14) show that there is slightly more difference between the effectiveness of smoke alarm types when a day or night situation is applied.

The maximum difference was with a nighttime situation when the combined smoke alarm option turned out to be 4.6% more effective than the ionisation one. For situations where there is no smoke alarm, 33% of humans would detect the fire through sound during the day and just 21% during the night. This highlights the importance of having a smoke alarm installed particularly if the dwelling is occupied during the night.

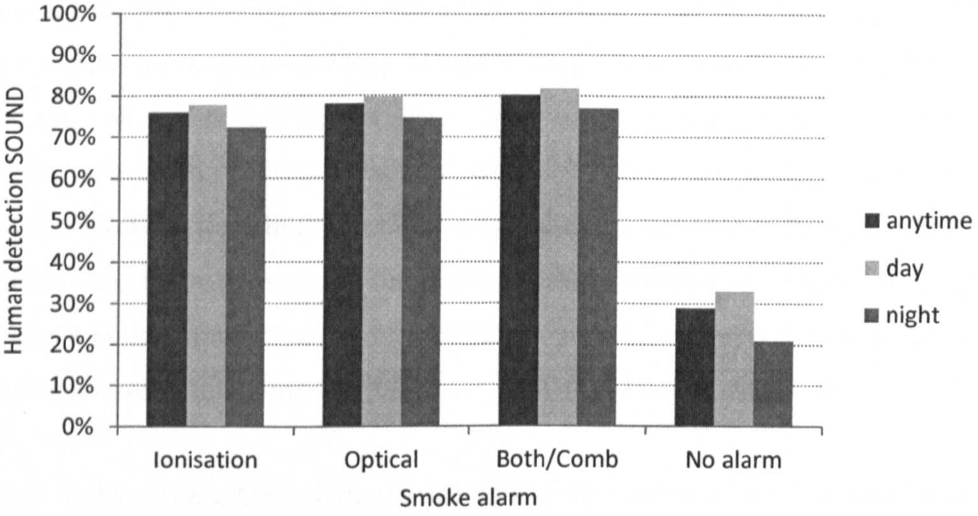


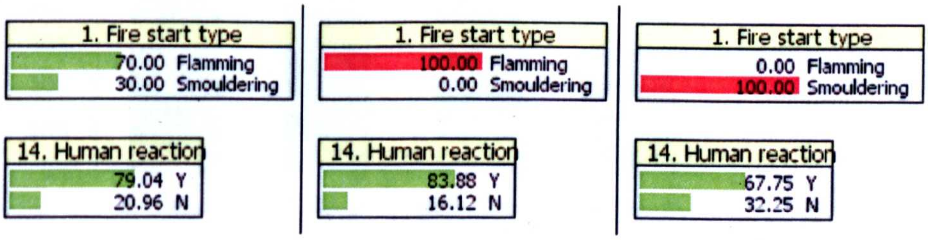
Figure 4.14. Posterior probabilities for "Human detection SOUND" with evidence inserted for "Smoke alarm installed" and "Time of day".

Case 3 – Flaming versus smouldering fires

Flaming fires are intrinsically different to smouldering fires with the latter only being possible on porous solids such as cotton or polyurethane foam. Within dwellings the development and often the consequences of each type of fire can be quite different. The rate of smouldering is governed by the ability of air to penetrate the porous fuel. The heat and carbon monoxide released from smouldering is far lower than from flames (National Institute of Standards and Technology, 2007). The smoke particles in a smouldering fire are relatively large and heavy smoke layers tend to accumulate well below the ceiling. Conversely flaming fires develop very quickly giving off more heat and smoke which rises rapidly to the ceiling; the smoke particles here are relatively small. Flaming fires would thus appear more dangerous, however smouldering fires are far more difficult to detect unless suitable devices are installed. To this end this case study investigates the ability of humans to react to both types of fire before they have grown to be 1 metre in diameter after which escape becomes very difficult.

Test 3.1: This test is a straight-forward comparison between the ability of humans to react to both flaming and smouldering fires. The tables below provide the results (Table 4.9). The left set of tables shows the probability (79.04%) that a human will react to a fire situation when the type of fire is not known. The set of tables in the middle and right provide posterior probabilities for "Human reaction" when the type of fire is known. It is clear that a human is less likely to react in the event of a smouldering fire than a flaming one. Note that these figures reflect situations where the states of other variables are unknown, for example, where there is no information about smoke alarms, time of day, sprinkler systems, *etc*. The next test will examine situations where there is evidence for such variables.

Table 4.9. Table of results showing the effect of "Fire start type" on "Human reaction".



1. Fire start type
70.00 Flamming
30.00 Smouldering

14. Human reaction
79.04 Y
20.96 N

1. Fire start type
100.00 Flamming
0.00 Smouldering

14. Human reaction
83.88 Y
16.12 N

1. Fire start type
0.00 Flamming
100.00 Smouldering

14. Human reaction
67.75 Y
32.25 N

Test 3.2: This test involved investigating the impact of different types of smoke alarm on human detection through sound given a specific type of fire. To recapitulate, ionisation smoke alarms are designed to respond faster to flaming fires and optical ones to smouldering fires. The chart below (Figure 4.15) reflects this fact and highlights the relatively poor performance of ionisation smoke alarms in smouldering fire situations compared to optical alarms in flaming fire situations. A human may also detect a fire through other sounds other than a smoke alarm; this is given by the 'no alarm' bars in Figure 4.15. In 'no alarm' situations it is evident that smouldering fires are harder to detect.

If these two findings are coupled, a) ionisation smoke alarms under performing in smouldering fire situations, and, b) smouldering fires being harder to detect compared to flaming fires in the absence of an alarm, then the case for installing an optical alarm over an ionisation one is justified from a technical stance. It is worth mentioning at this point that optical smoke alarms cost more than ionisation ones. Thus the following question can be raised: *Does the extra cost of an optical smoke alarm justify the potential benefits?* This could be answered from the perspective of an individual who is considering installing a smoke alarm in his/her dwelling, or from the perspective of an organisation like a FRS which have fire safety campaigns to plan. This cost-benefit analysis is discussed further in Chapter 5.

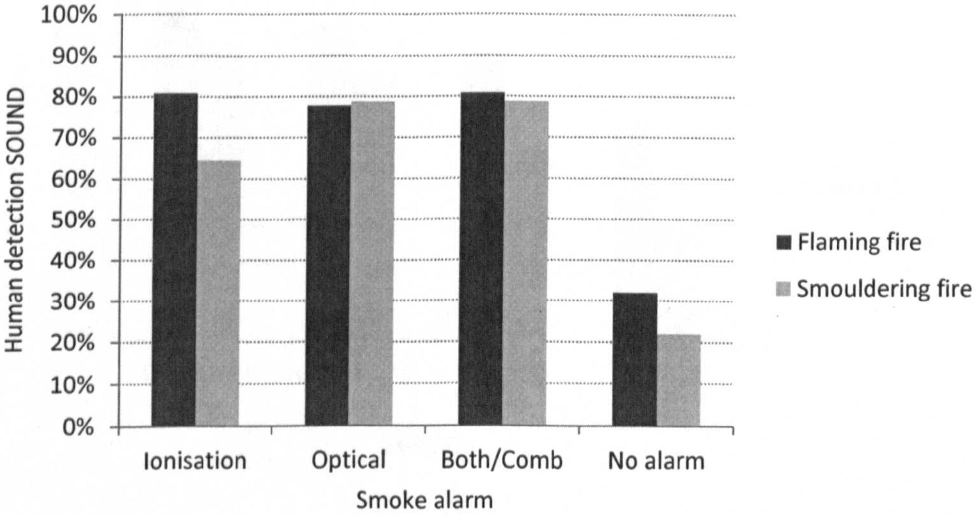


Figure 4.15. Posterior probabilities for "Human detection SOUND" with evidence inserted for "Fire start type" and "Smoke alarm installed".

Test 3.3: This test compares human reaction during a combination of flaming and smouldering fire situations, occurring during the day and night, with and without smoke alarms. The ability of a human to react to a fire can be impaired during the night as demonstrated in Case 1. It is also known that not having a smoke alarm significantly decreases the likelihood of early human reaction. The chart below (Figure 4.16) combines these variables into 4 situations and applies them to both flaming and smouldering fire events to see how human reaction varies. The results show that not having an alarm dramatically decreases the chance of early human reaction, particularly for smouldering fires. Furthermore, for nighttime situations where there is no smoke alarm present, the probability of human reaction during a smouldering fire is nearly half compared to a flaming fire. Another important observation is the drop in human reaction during nighttime situations. This fact is already known, but an interesting finding is that the difference in human reaction probability between day and night situations is far greater when there is no smoke alarm present.

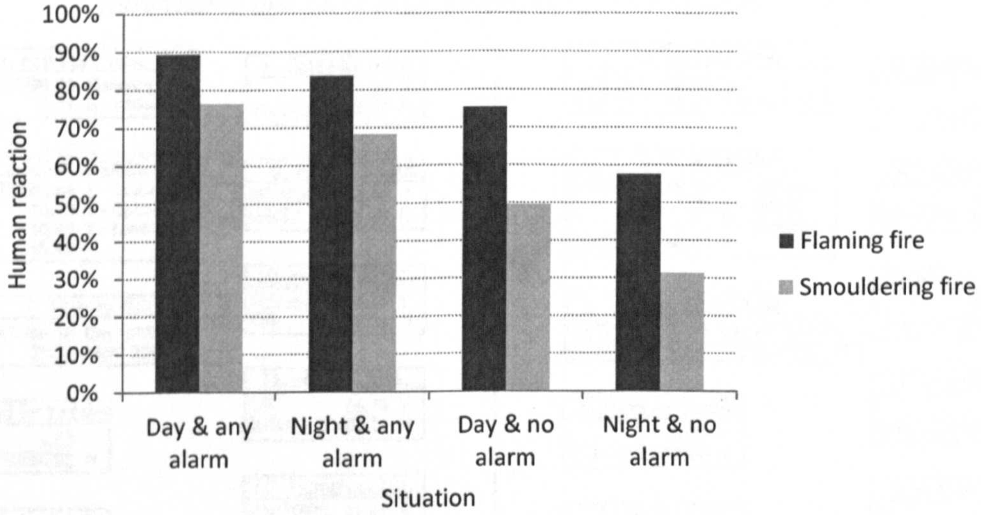


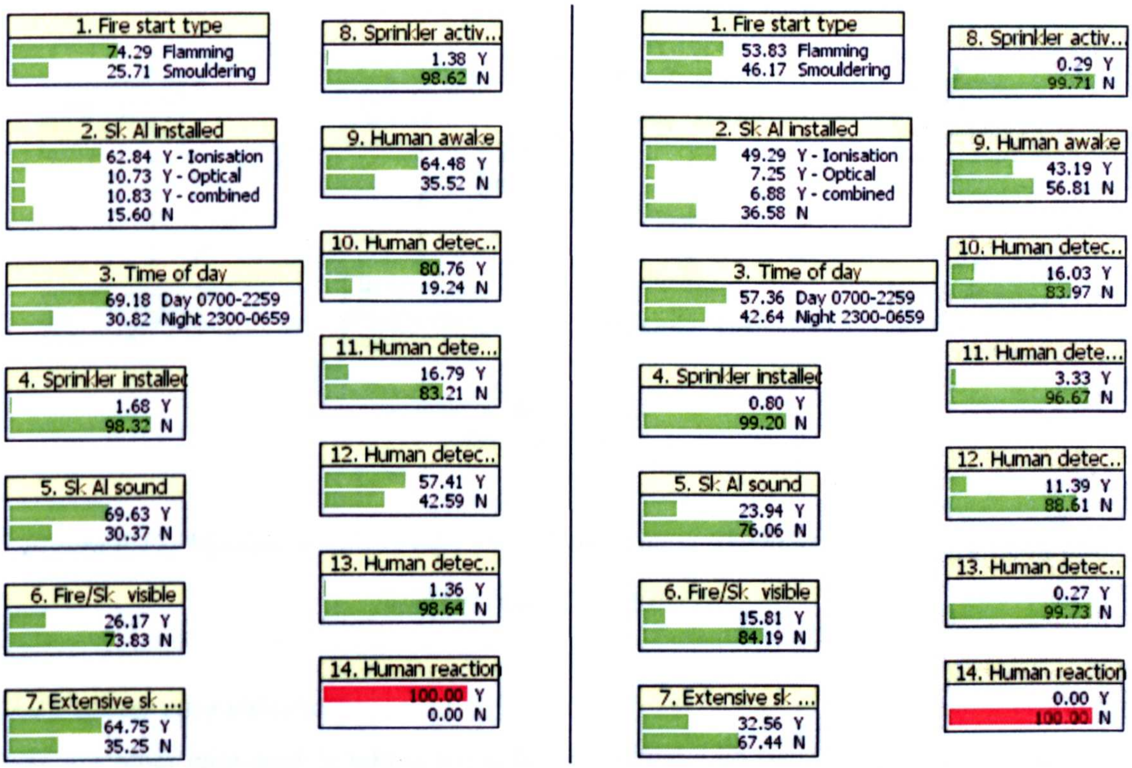
Figure 4.16. Posterior probabilities for "Human reaction" with evidence inserted for "Fire start type", "Smoke alarm installed", and "Time of day".

Case 4 – Investigating the causes of no human reaction

The final case study analyses what occurs throughout the network when evidence is inserted into the focus node "Human reaction". The idea is to provide information on what is the most probable scenario if there was no human reaction, including what may have gone wrong. Conversely when there is human reaction, the most likely scenario including what went right can be determined.

Test 4.1: The test results are shown below (Table 4.10), with the left and right set of tables representing situations where human reaction is successful and unsuccessful respectively. In terms of the scenario, when human reaction is successful it will most likely be a daytime (69%) flaming fire (74%); although this majority is maintained for the case of unsuccessful human reaction, the likelihoods drop to daytime (57%), flaming fire (54%). In terms of failures leading to unsuccessful human reaction, there is a notable increase in the probability of no smoke alarm sound 76%, compared to 30% in cases of successful human reaction.

Table 4.10. Table of results investigating the possible causes of "Human reaction" success (left set of tables) and failure (right set of tables). (To identify nodes whose names are not fully visible and for a node description, refer to section 4.4.1).



1. Fire start type
74.29 Flamming
25.71 Smouldering

2. Sk Al installed
62.84 Y - Ionisation
10.73 Y - Optical
10.83 Y - combined
15.60 N

3. Time of day
69.18 Day 0700-2259
30.82 Night 2300-0659

4. Sprinkler installed
1.68 Y
98.32 N

5. Sk Al sound
69.63 Y
30.37 N

6. Fire/Sk visible
26.17 Y
73.83 N

7. Extensive sk ...
64.75 Y
35.25 N

8. Sprinkler activ...
1.38 Y
98.62 N

9. Human awake
64.48 Y
35.52 N

10. Human detec..
80.76 Y
19.24 N

11. Human dete...
16.79 Y
83.21 N

12. Human detec..
57.41 Y
42.59 N

13. Human detec..
1.36 Y
98.64 N

14. Human reaction
100.00 Y
0.00 N

1. Fire start type
53.83 Flamming
46.17 Smouldering

2. Sk Al installed
49.29 Y - Ionisation
7.25 Y - Optical
6.88 Y - combined
36.58 N

3. Time of day
57.36 Day 0700-2259
42.64 Night 2300-0659

4. Sprinkler installed
0.80 Y
99.20 N

5. Sk Al sound
23.94 Y
76.06 N

6. Fire/Sk visible
15.81 Y
84.19 N

7. Extensive sk ...
32.56 Y
67.44 N

8. Sprinkler activ...
0.29 Y
99.71 N

9. Human awake
43.19 Y
56.81 N

10. Human detec..
16.03 Y
83.97 N

11. Human dete...
3.33 Y
96.67 N

12. Human detec..
11.39 Y
88.61 N

13. Human detec..
0.27 Y
99.73 N

14. Human reaction
0.00 Y
100.00 N

Test 4.2: Further evidence can be entered into the model to analyse particular scenarios. This test presents a potential real world scenario in which there has just been a dwelling fire and the occupants failed to react. The incident occurred during the night and evidence confirms that it started as a flaming fire. It is also known that a few days earlier the occupant installed a new optical smoke alarm; there is no sprinkler system in the property. An investigation is opened and the likelihood of the smoke alarm failing is analysed. The results are shown below through monitor windows displayed over the network (Figure 4.17). The posterior probability for node 5 indicates that the smoke alarm probably failed (60%). Such a finding is important since it could justify conducting an investigation into the origin of the smoke alarm. This simple case study demonstrates another way in which part I of the model could be used.

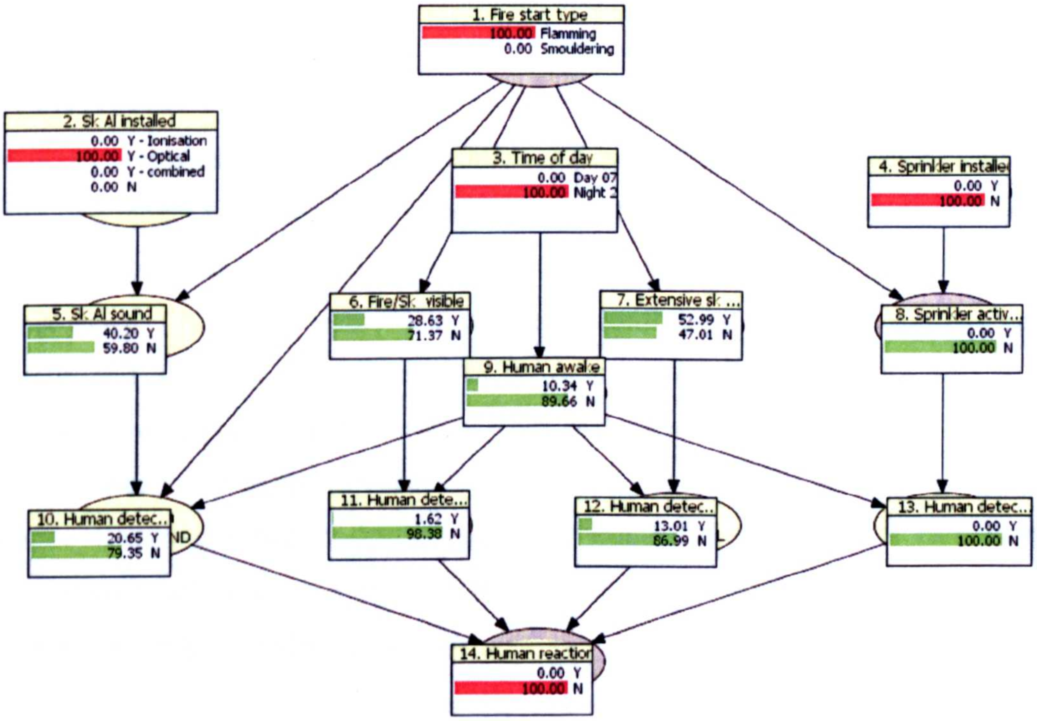


Figure 4.17. Monitor windows over the BN displaying likelihoods of why the occupant failed to react during the fire.

4.7.2 Further case studies

There are other case studies which could be conducted with part I of the model. One such example could be investigating the effect within a dwelling that a sprinkler system might have on alerting a human in case of fire. Sprinkler systems are designed to be a fire control measure, but they could potentially also serve as a fire cue, warning a dwelling occupant by spraying water on them. Another possible study could be investigating the effect temporary loss of hearing might have on a person within a fire situation. In this case node 10 would be set to "No" and posterior probabilities examined under different scenarios.

Case studies such as the ones described here can be conducted for each of the three parts of the model. What will be interesting is the integration of the model parts into one unit so that complete case studies can be carried out; these finding are presented further ahead within this thesis.

4.8 SENSITIVITY ANALYSIS

Sensitivity Analysis (SA) is fundamentally a measure of how responsive or "sensitive" the output of a model is to variations in the inputs. Understanding how a model can respond to changes in its parameters is of great important in maximizing its potential and ensuring correct usage. SA can also provide a degree of confidence that the model has been built correctly and is working as intended. In the context of this research, SA will be used to determine how responsive the output or focus node is to variations in other nodes. SA can also be viewed as a measure of dependence between selected input nodes and the output of a network. Knowing which nodes are the most influential can assist in experimentation, analysis, and further development of the model; nodes which are not important could subsequently be discarded or replaced.

SA has been conducted for part I of the model. The objective is to test the sensitivity of the focus node 14 "Human reaction", to changes in the input nodes 1 "Fire start type", 2 "Smoke alarm installed", 3 "Time of day", and 4 "Sprinkler installed". In short, SA is used to compare the degree of influence of the inputs on the output. The model can be tested to see how realistic it is by increasing or decreasing input variables that in real life impact considerably upon the output variable; if the model responds as expected then it resembles reality.

One way of undertaking the tests is to manually insert evidence into the input nodes, one at a time, and register the effect on the output node through its posterior probability. When doing this, the state of input variables would have to be increased and decreased individually by equal percentages, that is, the same absolute variation would have to be applied to each input node. This would allow a clear comparison of their impact upon the output node. In the tests undertaken however, this manual method was not used; instead the parameter sensitivity wizard within Hugin was applied. This allowed the task to be completed faster, though a manual test was carried out with the first input node to double check the results. Within Hugin, each input node was paired up individually with the output node "Human reaction" which was set to the state "yes". A state for each input node was then purposely selected so that it would have a positive impact on the output node. In this way a sensitivity value was obtained from Hugin for each input node and a graph constructed (Figure 4.18) to display the results. From Figure 4.18 it can be seen that the most influential variable on "Human reaction" is "Smoke alarm installed", while the least influential "Time of day". If "Smoke alarm installed" was to increase by 10% "Human reaction" would increase by 2.2%; however if "Time of day" was to increase by 10%, "Human reaction" would only increase by 0.9%. From the graph it is also evident that the sensitivity function is a straight line. The sensitivity values computed by Hugin are provided in Table 4.11. The higher the value the more influential the input node is on "Human reaction".

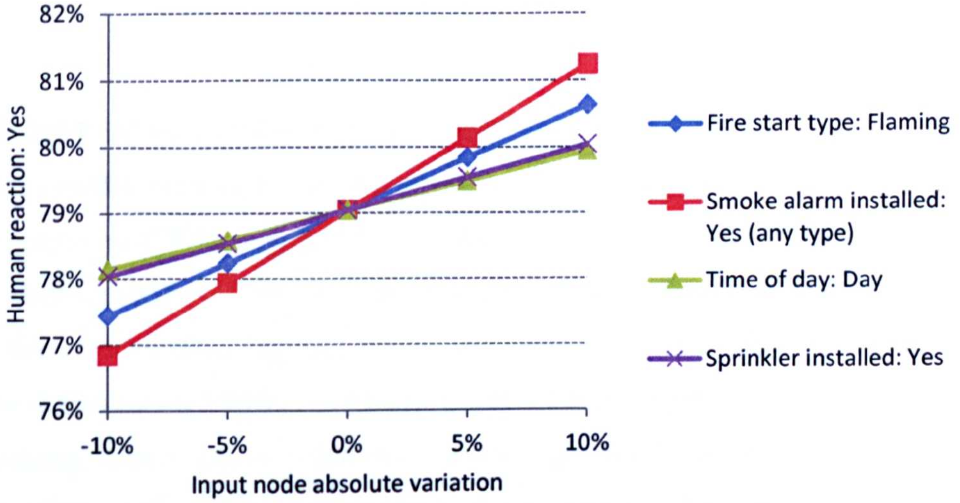


Figure 4.18. Sensitivity functions of the four root nodes on "Human reaction".

Table 4.11. Sensitivity values for four input nodes acting upon the output node "Human reaction". Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Smoke alarm installed: Yes (any type)	0.22
Fire start type: Flaming	0.16
Sprinkler installed: Yes	0.10
Time of day: Day	0.09

The input variables involved in the SA are all root nodes. Of the four, only "Smoke alarm installed" and "Sprinkler installed" can be altered by reviewing fire safety arrangements. Based on the SA, from a human reaction perspective, it is evident that increasing smoke alarm installations within communities would be more effective than installing more sprinkler systems: Costs are not taken into account at this stage.

Subsequent chapters will integrate all three parts of the BN model. It will be necessary to undertake a SA involving the whole model. In this way the importance of smoke alarms, sprinkler systems, miscellaneous fire safety measures, and FRS intervention, can be examined from a holistic risk assessment perspective, with the focus placed upon the output nodes involving the fire consequences.

4.9 FURTHER DEVELOPMENTS OF PART I OF THE MODEL

Part I of the model could be further developed to investigate in greater detail specific issues. One interesting modification would be to make "Time of day" a parent node of "Fire [start] type" as shown in Figure 4.19. The reasoning behind this is that the probability of having a flaming fire or a smouldering one varies according to the activities within the dwelling which are themselves a function of "Time of day". For example, the most frequent cause of fire is cooking; what is known is that this activity is generally carried out during the day and results in a flaming fire. If this was modelled the probability of having a flaming fire versus a smouldering one would increase further during the day whilst decreasing during the night.

That said, more needs to be known about the day / night effect on the probability of different types of fire before including it in the model.

Another possible modification to the model could be to include data on the frequency of fires. A node representing the probability of "Fire start per year" could thus be included (Figure 4.19); what is known is that the majority of fires occur during the day. Thus "Time of day" would also become a parent of "Fire start per year" if this was included within the model.

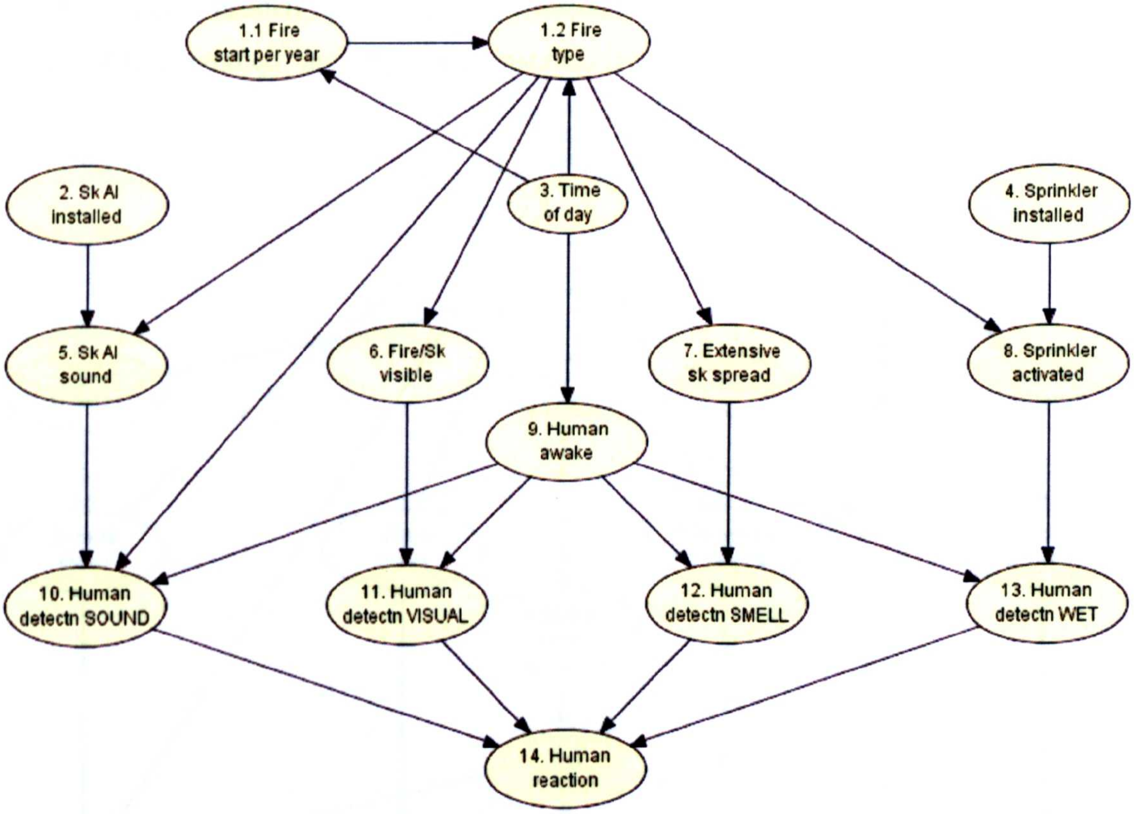


Figure 4.19. Modified version of part I of BN model featuring the addition of the node "Fire start per year". Note that the node "Time of day" is now linked to nodes 1.1 and 1.2.

Another interesting variation to the model which would impact many variables is the addition of a node representing the "Index of Multiple Deprivation" (IMD). These indices are the Government's official measure of multiple deprivation at LSOA level (Smith *et al.*, 2008; Communities and Local Government, 2007). This index would give the model a social perspective since it brings together 37 different indicators which cover specific aspects or dimensions of deprivation. The indicators fall into the following categories: Income, Employment, Health and Disability, Education, Skills and Training, Barriers to Housing and Services, Living Environment and Crime. The indicators are weighted and combined to create the IMD; Chapter 2 provides further detail. Reports have been published which link the indices to the frequency of fires, among other things. Figure 4.20 provides a view of how part I of the BN could be modified to include a social aspect. Four new nodes have been added headed up by the "Deprivation index" which has also been connected to "Smoke alarm installed" and "Sprinkler installed".

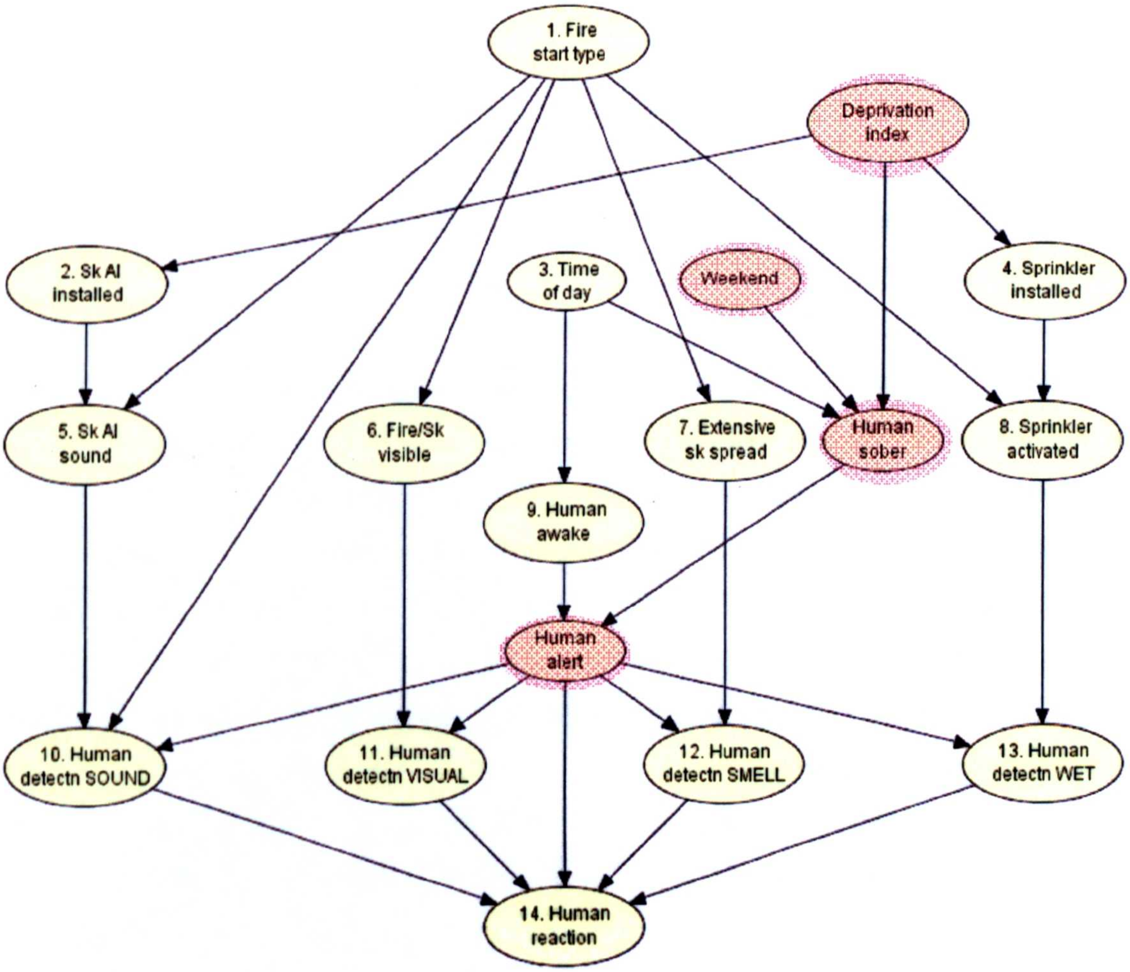


Figure 4.20. Modified version of part I of BN model featuring four new nodes (highlighted in red): "Deprivation index", "Weekend", "Human sober", "Human alert".

Other variations to the model could be made regarding the state of the occupants, for example nodes could be added representing physical impairments or even alcohol / drug abuse, the latter of which could be linked to the IMD. In the case studies above, fire cues do not always lead to human detection. Factors which may stop human detection from occurring include sensory impairments such as deafness, blindness, anosmia, *etc.* If this subject was to be investigated further part I of the model could be developed to include nodes representing these sensory impairments. Studies could then be conducted to assess the potential increased risk from fires for people with sensory impairments. This could serve as a tool to determine which groups should be targeted first in campaigns such as the Home Fire Safety Check.

4.10 CONCLUSIONS AND BRIEF DISCUSSION

This chapter has introduced the Bayesian network technique to model in three parts the development of fire within a generic dwelling. It has been argued that the diversity and complexity of fire scenarios makes them often unpredictable, which, when coupled with a lack of reliable data means that conventional risk assessment methods cannot always be applied. On the back of this, part I of the model (which deals with initial fire development and human reaction) has been used to demonstrate that BNs can provide an effective and adaptable method for determining the likelihood of events of interest under uncertainty. The model can be used to investigate various scenarios and to test if current safety arrangements can be improved. Before any results were generated several tests were undertaken to validate the model (Section 4.6). Following this, case studies were conducted (Section 4.7) which delivered some interesting findings; some examples are detailed below:

Case 1 – shows that a human's ability to detect a fire through sight and smell drops considerably during the night, particularly when compared to human detection through sound. This point highlights the importance of having an audible fire alarm within dwellings especially for nighttime situations.

Case 2 – concludes that having a combined smoke alarm is more important particularly if a dwelling is occupied by night. Not having an alarm has a greater negative impact on human reaction at night than during the day.

Case 3 – combines the significance of fire types, smoke alarm, and the time of day, concluding that humans are far less likely to react during a smouldering fire than a flaming one, but that this difference is far greater when there is no smoke alarm and it is night; for nighttime situations where there is no smoke alarm present, the probability of human reaction during a smouldering fire is nearly half compared to a flaming fire.

Case 4 – demonstrates how the model could be used during a fire investigation. A situation is presented in which "Human reaction" fails and it is found among other things that there was a 60% chance of no smoke alarm sound.

A SA has been carried out to determine how responsive the output of part I of the model is to variations in the inputs and hence validate that the model works as intended. This is an important exercise since it provides an indication of what the most important variables are in terms of the focus node. Furthermore, inputs or causes can be ranked in terms of their importance upon the output or consequence; in part I of the model "Human reaction" was most sensitive to variations in "Smoke alarm installed". The interesting and advantageous thing about SA of BNs is that they take into consideration the chain of events below the input node which lead to the output, thus presenting a closer approximation to reality.

The brief section titled "Further developments of part I of the model" (section 4.9) shows how additional hypothesis could be incorporated into the modelling and the purpose they would serve. There are many interesting possibilities which could be explored with relative ease now that the core structure of the model has been built. That said, before expanding the model, it is important to consider that it must remain practical from the perspective of generating results. Furthermore, too many variables which feature vague information may diminish the quality of the findings. The development of parts II and III of the model should shed further light into this.

CHAPTER 5 – BAYESIAN NETWORK MODELLING FOR FIRE SAFETY ASSESSMENT: PART II - OCCUPANT RESPONSE AND FURTHER FIRE DEVELOPMENT

SUMMARY

Chapter 4 introduces the four-part dwelling fire Bayesian Network and then develops part I of the model. Part II of the model is presented in Chapter 5 focusing on occupant response and further fire development whilst the fire is still of small to medium size. This part of the BN comprises of thirty four chance nodes and an additional four instance nodes which link it to part I of the model; there are eight output nodes, two of which are focus nodes examining occupant status and fire growth / flashover. The impact upon these focus nodes is examined in terms of the response of FRS's, occupant actions, fuel characteristics, property characteristics, and geographical area. Parameters relating to FRS response times are integrated into the model based upon the risk methodology of MFRS. Results demonstrate which parameters are more influential upon the occupant's chance of survival and the development of the fire. Case studies engaging with nodes from part I of the model reveal how smoke alarms, sprinkler systems, and time of the day affect the focus nodes. Following results and sensitivity analysis, the chapter continues by providing ideas on further developments for part II of the model including the addition of decision nodes to the network; the chapter concludes with a brief discussion highlighting the principal findings.

5.1 INTRODUCTION

This chapter continuous from where Chapter 4 left off by presenting part II of the BN model which deals with occupant response and further fire development. Representing the numerous events and parameters which interact during a dwelling fire in a single BN would require a huge network; this would not have been practical from the perspective of constructing and viewing the model, nor for the purpose of analysis of results for different phases of the fire. Hence, as explained in Chapter 4, a four part model was built with three core parts and one *fire time response module* which is presented in Chapter 7. Figure 5.1 provides a representation of the three core parts of the model (also presented in Chapter 4) but with part II highlighted.

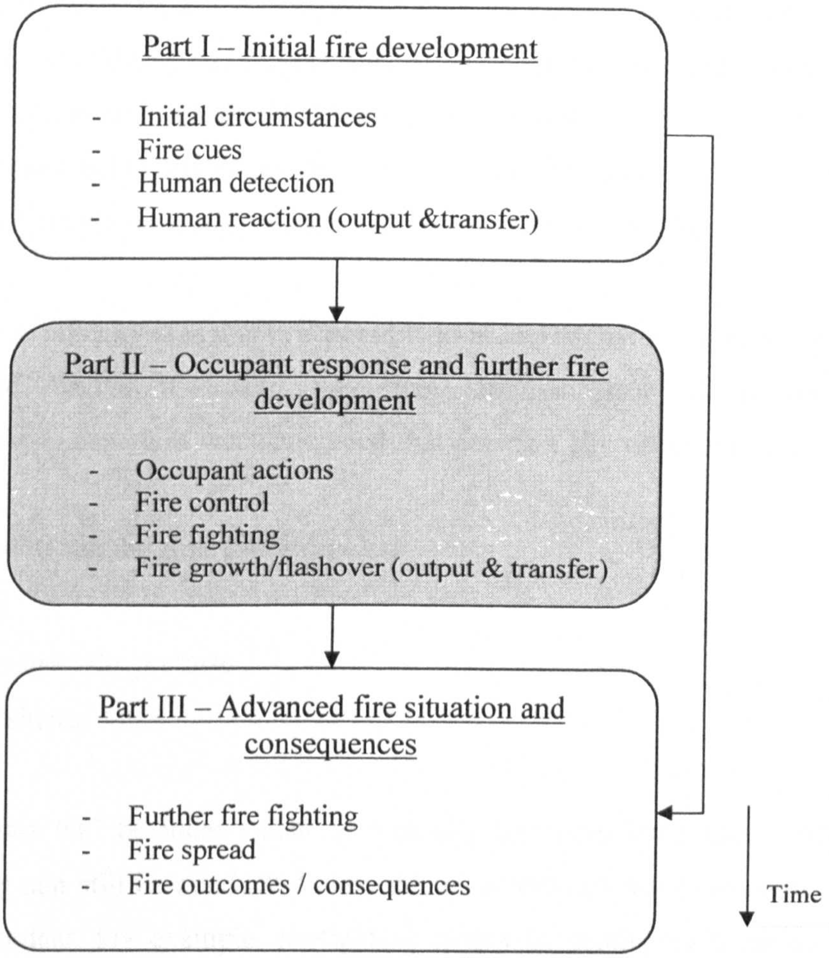


Figure 5.1. Flow chart of events within each part of the BN model

In part I of the model human reaction to fire cues was examined. Part II of the model now addresses, among other things, what follow-up actions an occupant may take in respect to the fire itself. It is important to understand human response to a fire as the actions undertaken may have a large impact upon the chance of survival. Modelling human reactions is complex at the best of times yet alone in life threatening highly stressful situations such as fire. Meacham (1999) discusses some of complexities of human behaviour and psychology involved in response to fires. At the start of a fire people are often bemused about what is occurring and often are slow to react until they actually perceive danger. Past experience and awareness to a situation have a part to play. Bryan (1991, cited in Meacham, 1999) stated that people have six basic inputs into their decision process: recognition, validation, definition, evaluation, commitment, and reassessment. Modelling human actions to such detail falls beyond the realm and objectives of this research project. Human behaviour at this level is however addressed in work by Nilsson and Johansson (2009), McEntire (2007), Shields and Boyce (2000), and Proulx (1995).

The approach taken in this model is that it is possible to model the effect of human reaction upon the chance of survival if broken down into common basic actions. Based on discussions with various experts it was concluded that during a fire occupant basic actions are to:

- Communicate or call the emergency services
- Fight the fire
- Escape or evacuate the premise
- Hide or seek shelter

Some of these actions will be independent or mutually exclusive from each other. For example, firefighting can still be conducted even though a 999 call has been made. Other actions will be dependent. For example, firefighting cannot be conducted if the action of escape has been undertaken. This is reflected in the *arcs* and CPTs of the relevant nodes in the BN.

Another area modelled in this part of the BN is further fire development. The aspects that are influential here are fuel characteristics, mitigating measures, and FRS response. Predicting fire growth can either be undertaken by dynamic modelling, or as in this case, through conditional probability assignment to the most important parameters. This part of the network also involves modelling FRS response time and its effect upon fire growth and rescue.

The outputs from part II of the model centre on occupant state and fire growth. The former is influenced by smoke which is also represented in the model. Chapter 2 discusses the effects of smoke and why it is considered more lethal than the fire itself.

The rest of this chapter presents a full account of part II of the BN (section 5.2), explains how data was constructed for some of the more complex nodes (section 5.3), presents calibration of the network through prior probability comparisons with statistics (section 5.4), develops several case studies (section 5.5), undertakes a sensitivity analysis (section 5.6), outlines potential further developments of part II of the model (section 5.7), and ends by presenting conclusions and a short discussion (section 5.8).

5.2 PART II OF THE MODEL – OCCUPANT RESPONSE AND FURTHER FIRE DEVELOPMENT

The underlying theory of BNs and a review of previous research are provided in Chapter 4. Constructing part II of the model was undertaken following the step-by-step procedure described in section 4.3.1.1 of Chapter 4. In part II of the model the network begins at the moment of human reaction within a fire and continues up to the point of fire stage 2 as described in section 5.2.2. The focus is on the state of the occupant at fire stage 2 and fire growth.

5.2.1 Continuous data represented through discrete nodes

Part II of the model includes five time-based nodes. Time is inherently continuous so would best be represented through a continuous chance node. Although continuous nodes, representing random variables with Gaussian (normal) conditional distribution functions, can be used in the Hugin software, there are some restrictions on their application. This is partly because the underlying theory is still being developed (HUGIN EXPERT A/S., 2012). The restrictions are listed below:

- The only continuous chance nodes currently supported in Hugin represent variables with Gaussian (normal) distribution functions.
- A continuous chance node cannot be a parent of a discrete chance node even though the opposite is possible.
- Continuous nodes cannot be used in influence diagrams. This means that continuous nodes cannot exist in a network also containing utility nodes or decision nodes.

Parts II and III of the model contain some nodes which represent continuous data but these are configured as parent nodes of discrete nodes. Since a continuous node cannot be a parent of a discrete node the continuous data has had to be represented through a discrete node using data ranges as states; this could be referred to as a form of discretization of continuous data. A full description of part II of the model with details of the nodes follows in section 5.2.2 but before then a list of the nodes with continuous data represented by discrete nodes is provided below:

- 999 call
- MACC dispatch / call processing time
- Preparation + travel time appliance 1
- Response time appliance 1
- Appliance 1 at scene

5.2.2 Assumption and limitations

5.2.2.1 Space / time limitations

One of the purposes of the model is to be able to calculate the impact of fire on occupant reaction, actions, and ultimately life safety. To address this, the model incorporates various time-based probabilities. The model has therefore a timeline which governs the series of potential events it represents. Certain nodes in parts II and III of the model are limited by time even though they do not contain time specific data. This has been achieved by establishing three fire stages as described below:

Fire stage 1 (denoted as F stage 1 or FS1 on BN): During fire stage 1 the fire will typically be relatively small when compared with the size of the dwelling; this is not to say that the rate of growth is slow for it may be a fast growing fire. The fire type can either be flaming or smouldering and would be contained to the room of origin. The first attempt at extinguishing the fire will take place within this fire stage, undertaken by the occupant; it is highly unlikely that the first FRS appliance would have arrived. The time boundary for fire stage 1 is two minutes from the moment of human reaction.

Fire stage 2 (denoted as F stage 2 or FS2 on BN): At fire stage 2 the fire would be of small to medium size meaning that it could potentially fill the entire room of origin and threaten to spread further. By this stage the fire type would be exclusively flaming with any smouldering fire having either been put out or evolved into flames if no action was taken. The first attempt at putting out the fire will have already taken place and the outcome would be known. If the fire was extinguished, then fire stage 2 would not arise, otherwise the fire would continue. At this stage smoke and heat would begin posing significant problems to evacuation, rescue, and survival. Flashover may also occur during this fire stage. It is likely the first FRS appliance would have arrived and intervened by this stage. The time boundary for fire stage 2 is up to five minutes.

Fire stage 3 (denoted as F stage 3 or FS3 on BN): Fire stage 3 represents an advanced phase of the fire in which its size could range from small to large depending on various factors such as how effective fire fighting measures had been. A large fire implies fire that has spread from the room of origin into other compartments or even an adjoining dwelling. By this stage FRS appliance 1 and additional support would be highly engaged in attacking the fire and rescuing any occupant. Fire stage 3 is the final phase of the fire and there is therefore no time boundary.

Note that some nodes are applicable to one particular fire stage for example "Self-evacuation fire stage 1" while other nodes may cover two fire stages for example "Rescue completed fire stage 1 and 2". The latter simply means that rescue could have been completed during either fire stage 1 or 2.

5.2.2.2 Notes on aspects of the model data

Some remarks need to be made with regards to the uniformity of data. Statistics exist in a variety of forms and originate from many sources. In a study as inclusive as the one being conducted, it will never be possible to obtain data sets from complete homogeneous origins. Further work can always be conducted in future on improving the consistency of the origin of data from different parameters. The following paragraphs highlight some of the disparity between data sets.

Data samples

It is important to point out that certain statistics will never be completely representative of reality. For example, it has been reported that approximately 90% of domestic fires never come to the attention of FRS's, either because they extinguish themselves or because the occupant extinguishes them without professional assistance (Marriott, 1993). If human behaviour data is considered, the actions undertaken during those 90% of cases may be quite different to the 10% attended by FRS's. It could transpire that the occupants nearly always decided to tackle the fire in those missing 90% of cases; if these observations were incorporated into the findings already known the overall picture may be slightly different. The data within the model is partly comprised of dwelling fire statistics; it is important to note that such data will be limited to incidents attended by FRS's, when this information is recorded, and hence there will not be a record of many minor unreported fires.

Regional and national data

Another important consideration with regards to the data sets is that some of it is representative of Merseyside and others of the UK. For example crew preparation and travel time of appliances has been modelled on information for Merseyside; however data on levels of urbanisation and housing (bungalows) is based on UK statistics. The most important parameters in respect of occupant survival are those associated with FRS response, thus they dominate the parameters associated with urbanisation and housing. Consequently the model can be considered a more accurate representation of the Merseyside sub-region than the UK.

Regional differences with regards to other parameters such as human behaviour during a fire, fuel combustion, and smoke lethality, can be considered negligible.

Age of data

There are differences in the age of the data used within part II of the model. The majority of data is taken from sources post 2006. Data on nodes regarding performance of FRS's, housing, and other rapidly evolving factors has been obtained from recent periods. On the other hand data for some parameters is slightly dated, for example certain information on aspects of fire growth has been obtained from studies prior to 2000; however such variables changed very little with time thus the effect upon the results should be negligible. MFRS experts were consulted for reassurance for cases when data was thought to be dated.

Subjective v hard data

Some nodes incorporate hard evidence based statistics however other nodes are based on subjective expert judgement. Combining information in this way has allowed uncertainty to be overcome for situations where no information really exists. This will not pose a problem in terms of the validity of results but it is nevertheless worth keeping in mind when interpreting the information.

5.2.3 Nodes and structure

Part II of the BN model (Figure 5.2) is designed to represent occupant response and further fire development. The function of this network is four-fold: firstly, it can be used to investigate the effects of human actions namely those of an occupant, a passerby, and FRS's as a unit; secondly, the influence of the environment can be investigated in terms of fuel load, fuel toxicity, fire fighting devices, and floor level; thirdly, the development of fire can be analysed in terms of its interaction with numerous variables including FRS intervention; fourthly, the effect of fire development upon evacuation, rescue, and survival can be examined. The focus of this part of the investigation is fire development and occupant survival assessed through the nodes "Fire growth/flashover" and "State of the occupant fire stage 1&2" respectively.

There are four transfer nodes, known as instance nodes in the Hugin software, which link part I to part II of the model. These nodes are "Human reaction", "Time of day", "Fire start type", and "Sprinkler activated". Through these nodes any evidence inserted into part I of the model will result in updates to posterior probabilities of part II.

From part II of the network there are in turn eight transfer nodes which link up to part III, these are "999 call", "Risk map score", "MACC dispatch / call processing time", "Appliance 1 at scene", "State of occupant fire stage 1&2", "Fire extinguished", "Fire growth/flashover", and "Smoke lethality". Part II consists in total of thirty four chance nodes each of which has between two and four states.

To comprehend how the model works and why it has been set-up in the way it has, the logic behind each node needs to be explained. Furthermore it is also necessary to understand what each state means, what the assumptions are, how each node interplays with its parent and child nodes, and how the data for the CPTs have been built. Part II of the model has a greater number of nodes and a higher level of complexity in the way they relate or influence each other compared to part I. A more detailed account of each node is thus necessary. The thirty four nodes have been categorized into *pre-conditions, human actions, FRS interaction,* and *occurrences / fire development.* The following is a description of each node arranged firstly according to category and secondly according to chronological interaction within the network.

Pre-conditions:

1. Location [states: urban, suburban, rural] – This parentless chance node or root node describes the level of urbanization in which the dwelling is located. The classification of the three states is taken from the English Housing Survey 2008 (Communities and Local Government, 2010c): urban encompasses city centre and other heavily built up areas in which residential areas are mixed in with offices, shopping centres, and various public buildings; suburban covers built up areas consisting principally of residences; rural refers to rural residential, village centre, and simply rural zones which are not built-up. A brief account of type of areas and other characteristics of the UK's dwelling stockpile is provided in Chapter 2.
2. Occupant fire trained [states: Yes, No] – This parentless chance node represents the dwelling occupant having some sort of formal or informal fire safety training and experience. This could include completing a course, training through television, attending a demonstration about fires, attending an FRS open day, or reading relevant literature. Data for this node was compiled from interviews conducted by Marriott (2003).
3. Fire fighting equipment [states: Yes, No] – This parentless chance node describes the presence of some sort of firefighting equipment within the dwelling. This includes items such as an extinguisher, a fire blanket, and a hose. Data for this node with regards to dwellings with fire extinguishers was obtained from a report by Reynolds (2002). Information for other types of firefighting equipment was compiled from personal communication with experts.
4. Fuel load [states: High, Low] – This parentless chance node describes the amount of combustible material (furniture, books, wallpaper, *etc.*) in the fire room of origin in relation to the size of that room. Fuel load is a governing parameter affecting the severity and duration of a fire (Yung, 2008; Melinek, 1993). The lower the amount of fuel the less vigorous the development of a fire. According to Yung (2008), the mean fuel load value for dwellings is 780 MJm-2. There is however almost no data on fuel load by room because of the time it would take to establish such values in statistically significant quantities; the marginal probabilities for this node are

therefore set at [High 0.5, Low 0.5]. Nevertheless it is important to include this node in the network for cases when fuel load data becomes available.

5. Fire retardant materials [states: Yes, No] – This parentless chance node represents the fire retardant properties of fuel sources within the fire room of origin. Fire retardant materials are those which have a reduced degree of flammability and hence inhibit fire growth. Fire safety regulations ensure most furniture today is manufactured with fire retardant materials; it is unlikely old furniture will have such properties. Chapter 2 provides further information on associated legislation such as the Furniture and Furnishings (Fire) (Safety) Regulations 1988.
6. Fuel combustion [states: High, Low] – This chance node represents the degree of fuel combustion based upon the speed and sustainability of burning. The first of these two ingredients is a function of the flammability of the fuel source / materials which in turn is a function of its properties (porosity, chemical composition, relative water content, *etc.*); the second ingredient is a function of the quantity and positioning of the fuel source. The conditional probabilities of "Fuel combustion" are set according to the state of its parent nodes "Fire retardant materials" and "Fuel load".
7. Drills [states: Yes, No] – This parentless chance node describes the occupant pre-condition of having undertaken any sort of fire evacuation drill. This could include basic knowledge such as being aware of the most convenient exit route for a particular situation *e.g.* kitchen fire - exit via back door, fire on stairs – exit via main bedroom window onto garage roof and swing / lower off roof end onto lawn. Other relevant information may include knowing to keep low to avoid smoke, having an idea of distance between rooms in case of darkness, using a wet towel to shield oneself from heat, among other information.
8. Full mobility [states: Yes, No] - This parentless chance node represents the mobility status of the occupant. Full mobility would not be possible if for example a person was carrying an injury, was very elderly, or was partially disabled. This node does not account for occupants who are severely disabled who would require rescue from

the onset of a fire. An occupant who was not fully mobile would not be as agile or fast and therefore would have a lower probability of successful escape.

9. Ventilation [states: High, Low] – This parentless chance node represents the level of ventilation or air supply to the fire. Data for this node was unavailable but in this study it will be assumed that ventilation conditions are relatively uniform across dwellings. The node has been incorporated for cases when experimentation with ventilation is desired. Ventilation is dependent upon windows and doors being left open coupled with windy day conditions. This node would have more meaning within controlled environments such as industrial premises and enclosed buildings where ventilation can be managed.
10. Fuel toxicity [states: High, Low] – This parentless chance node represents the level of toxicity of the fuel. The type of combustibles in a dwelling, for example furniture, plastics, carpets, paper, *etc.*, affects the level of toxic gases generated. In any dwelling there is usually more than one type of fuel present, thus any fire would burn with the characteristics of the combined types of fuel; further information is provided in Chapter 2. Data for this node was not available in statistically representative form however, certain tendencies were discovered. An important finding was that the use of plastics in general has increased considerably since the 1970s which consequently has brought about an increase in the level of fuel toxicity in homes (Hofman *et al.*, 2007). Furthermore children's bedrooms are in particular very hazardous due to the accumulation of toxic fuels such as plastic toys, electrical devices, mattresses and upholstery. Babrauskas (1993) compares and assesses levels of toxicity in different materials. This node's marginal probabilities were put together using various findings within literature which in general indicate a high level of fuel toxicity within dwellings. A state of [High] fuel toxicity within a dwelling is taken as the presence of various sources of plastics, paper (books, magazines, *etc.*), electrical appliances, carpets, and various upholstery items. State [Low] is described as few plastics, few paper items, an absence of carpets, and in general minimalistic furnishing.

11. Bungalow [states: Yes, No] – This parentless chance node represents the probability of the dwelling being a bungalow. This node affects the probability of the occupant being on the ground level at the time of the fire. Bungalows are traditionally one floor constructions, however, it must be noted that a small percentage have second floor loft conversions. Data for this node was obtained from the English Housing Survey 2008 (Communities and Local Government, 2010c).
12. Risk map score [states: High, Medium, Low] – This parentless chance node represents the risk area in which the dwelling is located. MFRS have developed a risk model which classifies all LSOA within Merseyside into high, medium, and low risk levels. The methodology and risk map which is produced are explained in Chapter 2, section 2.4.4. There are a total of 905 LSOAs in Merseyside 77 of which are high risk, 443 medium risk, and 385 low risk (MFRS, 2009). Since LSOAs are of similar size by population it can also be assumed that there are a similar number of homes in each area. Because of this the ratio of high : medium : low risk LSOAs, that is, 77:443:385 can essentially be used as the ratio of dwellings at high, medium, or low risk. Thus the probability of a dwelling being at high risk would be 77/905 = 0.0851, medium risk 443/905 = 0.4895, and low risk 385/905 = 0.4254. Since the target time of incident response by MFRS is based upon these three levels of risk, the probability of an appliance arriving at an incident within a given time band can be computed. The node "Risk map score" is therefore used to feed into the nodes "Preparation + travel time appliance 1" and "Preparation + travel time additional support" the latter of which features in part III of the model. "Risk map score" also acts as a transfer node into part III of the model.

Human actions:

13. Occupant on ground level [states: Yes, No] – This chance node describes the floor level on which the occupant is located at the time of the fire. This would affect both evacuation and rescue probabilities. The node's conditional probabilities are set according to the state of its parent nodes "Bungalow" and "Time of day" which is a transfer node from part I of the model. The CPT reflects the fact that during the

night nearly all people would be in their bedrooms. The majority of bungalows have only ground floor bedrooms whilst non-bungalows have the majority of bedrooms on the first floor (that is the second floor level). The CPT was built on this premise using statistics from the English Housing Survey 2008 (Communities and Local Government, 2010c). The data also accounts for people in non-bungalows spending more time on the first floor during the day compared to bungalows based on the assumption that non-bungalows have more space on first floors compared to bungalows which on most occasions do not even have a first floor.

14. 999 call [states: <1m, 1-3m, >3m] – This chance node represents the periods in minutes within which a person is likely to make a 999 call. Its conditional probabilities are set in line with its parent nodes "Human reaction" and "Passerby outside". The probabilities of a passerby dialling 999 are slightly lower than for an occupant since the former is outside the property therefore the effectiveness of all fire cues is smaller. In terms of the occupant, if this person is known not to be able to react then it is possible that the dwelling has an automated fire call system linked in with MACC. This node assumes that if there is no human reaction then a 999 call will eventually be carried out by someone external to the dwelling. Note that time is continuous in nature and would therefore be best represented by a continuous chance node, however, as previously mentioned in section 5.2.1 such a node cannot be a parent of a discrete node nor can it be used in a network containing utility or decision nodes. To get around this problem a discrete node was instead used with three possible states or time periods and conditional probabilities assigned based on expert judgement. The start time $t=0$ for this node is taken from the instance of "Human reaction". The node is also a transfer node into part III of the model.
15. Seek shelter [states: Yes, No] – This chance node represents the action by a human to find shelter within the dwelling; this behaviour is often associated with children who look for reassurance by hiding. Its conditional probabilities are set in relation to its sole parent node "Human reaction" derived from part I of the model.
16. In-house firefighting [states: Yes, No] – This chance node represents the action of the occupant fighting the fire. Data from Reynolds (2002) indicates that 13% of

people fight fire upon discovery; however the report is on fatal dwelling fires. According to expert opinion, if data from non-fatal fires and fires not reported were included the percentage would be higher. The conditional probabilities of "In-house firefighting" are set according to the state of its parent nodes "Human reaction" and "Seek shelter", the former being a transfer node from part I. "Seek shelter" and "In-house fighting" are mutually exclusive thus if the former occurs the latter cannot happen.

17. Self-evacuation fire stage 1 [states: Yes, No] – This chance node describes the action of the occupant immediately leaving the dwelling during fire stage 1 as described in section 5.2.2.1. Its conditional probabilities are set according to the state of its parent nodes "Human reaction" (transfer node from part I), "In-house firefighting", and "Seek shelter". The latter two of these nodes are mutually exclusive with "Self-evacuation fire stage 1"; in other words the occupant can select only one action from firefighting, seeking shelter, or evacuating. The sum of the probabilities of these three nodes when in positive state is 1.
18. Self-evacuation fire stage 2 [states: Yes, No] – This chance node describes the action of the occupant leaving the dwelling at fire stage 2 which is described in section 5.2.2.1. Its conditional probabilities are set in line with the state of its parent nodes "In-house fighting" and "Fire extinguished"; the CPT is based on the premise that the node will be positive when in-house firefighting has occurred but the fire has not been extinguished.
19. Passerby intervention [states: Yes, No] – This chance node represents the passerby attempting to rescue the occupant should rescue be required. Its conditional probabilities are set according to the state of its parent nodes "Passerby outside", "Rescue required", and "Appliance 1 at scene"; the logic applied in setting this CPT is that the longer an FRS takes to arrive the greater the need to rescue someone as the fire grows. However once the fire has reached a certain size the probability of passerby intervention will actually begin to fall as the fire becomes more threatening to that person's safety.

FRS interaction:

20. MACC dispatch / call processing time [states: 0.75 (<1) minutes, 1.5 (1 to 2) minutes, 2.5 (>2) minutes] – This parentless chance node represents the time it takes from the receipt of an emergency 999 call at MACC to the moment when fire crews are notified; this time is also known as dispatch time. Time t=0 is set from the moment the 999 call is received by MACC. Notification of fire crews may occur by calling either a station or an appliance directly if it is mobile (refer to Chapter 2 for an account of mobilization procedure). Before any notification takes place the call handler must extract sufficient information from the caller with regards to the type of incident and its priority; FRS's have to deal with various types of incidents besides fires for example hazardous spills, entrapments, car accidents, *etc.*, as explained in Chapter 2. Next the location of the incident must be established at which time the nearest suitably prepared appliance is identified through MACCs Vision BOSS system and subsequently notified; the caller is kept on the line where possible. As the crew prepare and the appliance begins its journey to the location further details are obtained about the property and the people involved. After vital information has been collected the caller is often kept on the line to guide them on what steps to take and avoid the onset of panic. Data for this node was compiled from a questionnaire distributed to call handlers at Merseyside's MACC (see Appendix 7). Further details on how the CPT was built can be found in Appendix 8. Also note that this is one of the five discrete nodes in part II of the model representing a continuous variable as explained in section 5.2.1. The node in addition is a transfer node linking part II to part III of the model.
21. Preparation + travel time appliance 1 [states: <5m, 5 to 10m, >10m] – This chance node represents the time from when the fire crews of appliance 1 are alerted of the incident to when the appliance commander books the vehicle in attendance at the scene. In other words, it is the time taken for fire crews to prepare and get into the appliance at the station, plus the time it takes for the appliance to travel to the scene. Time t=0 is set from the moment the crews are notified of the incident by MACC. The reason crew preparation and travel time are grouped into one node is because

MFRS set and measure their response standards / time based upon the amalgamation of these two actions; the two actions are however modelled separately in part IV of the model that is the "Fire time response module", which attempts to model how various factors affect FRS response time. Part IV of the model is linked to an alternate version of part II of the model presented in Chapter 7. On Merseyside, the response standards in relation to fire are set according to the LSOA level of risk calculated using MFRS's methodology (see Chapter 2, section 2.4.4). The standards in summary specify the following:

- For High risk the first appliance must arrive within 5 minutes with additional support within 8 to 10 minutes.
- For Medium risk the first appliance must arrive within 6 minutes with additional support within 9 to 11 minutes.
- For Low risk the first appliance must arrive within 7 minutes with additional support within 10 to 12 minutes.

Emergency 999 call handling represented through the node "MACC dispatch / call processing time", is not included in the standards as call handlers must vigorously challenge all calls to ensure accurate information and filtering of malicious calls. Callers are therefore kept on the line for varying lengths of time and even whilst an appliance is being dispatched or in attendance. If call handling was included in the response standards it would be harder to establish where targets were being missed and what the associated reasons were. Call handling is therefore managed separately from fire crew response and hence represented through a different node. In the 'risk-map' linked part II of the model response time is based on the "Risk map score" node. The target of MFRS is to achieve the above response standards on 90% of occasions. Personal communication with various MFRS staff (Kellaway 2011, Pritchard 2011, Scarth 2011, and Fay 2010) confirmed that the performance during 2010-2011 was very close to 90%, *circa.* 91% to 92%. In this study it is therefore assumed that the standards will be achieved on 90% of occasions, therefore the conditional probabilities of this node are set in line with its sole parent node "Risk map score", based on that assumption. Note that there will be circumstances when the appliance called to the scene is already mobile, that is, not at the station. In such circumstances travel time is likely to deviate considerably compared to it being at the station. Furthermore crew preparation time would be zero. Such variations are considered to already be represented within the data adhering to the 90% performance criteria and thus the geographical location of the appliance is not considered separately in the network. Further explanation of how data for this node was put together is set forth in Appendix 8. Note also that this is one of the five discrete nodes representing a continuous variable in part II of the model as explained in section 5.2.1.

22. Response time appliance 1 [states: <5m, 5 to 10m, >10m] – This chance node represents the time from the instance the 999 emergency call is made to the time when the first FRS appliance arrives at the incident location. Response time is essentially the addition of MACC / dispatch time, crew preparation time, and travel time as outlined in Chapter 2. Time t=0 is set from the moment the 999 call is received by MACC. As with the two previous nodes this node is a measure of time in minutes and would require representation through a continuous node. Since this is not possible time bands are once again used as specified through the node's states. The node's conditional probabilities are computed in relation to the states of its parent nodes "MACC dispatch / call processing time" and "Preparation + travel time appliance 1". An explanation of how this is achieved can be found in Appendix 8.
23. Appliance 1 at scene [states: <5m, 5-10m, >10m] – This chance node represents the time taken for the first FRS appliance to arrive at the scene of the fire from the moment of human reaction, that is, from the moment the occupant is alerted of the fire. The time is hence an aggregation of the time taken by the occupant or a passerby to make a 999 call, the time for MACC to process the call information, the time for fire crews to prepare, and the time taken for the appliance 1 to travel to the location of the fire. The start time *t=0* for this node is taken from the instance of "Human reaction". This node's conditional probabilities are set according to the state of its parent nodes "999 call" and "Response time appliance 1"; further explanation of how data was put together is given in Appendix 8. "Appliance 1 at

scene" is important because it influences the probability of any rescue being completed as well as the probability of a passerby intervening in the rescue. The node is also a transfer node linking part II to part III of the model. Note that the node is one of the five discrete nodes representing a continuous variable in part II of the model as explained in section 5.2.1.

Occurrences / fire development:

24. Passerby outside [states: Yes, No] – This chance node represents the presence of a passerby outside the dwelling at the time when human reaction would take place, that is, once the fire cues have occurred. A passerby would thus also have a chance of becoming aware of the fire and hence interacting with the situation. Conditional probabilities are set according to the state of the parent nodes "Location" and "Time of day".
25. Fire type 2 minutes after detection [states: Flaming, Smouldering] – This chance node represents the type of fire burning two minutes after it has been detected, hence, it establishes for cases of smouldering fires if this has transformed into a flaming fire. This node is important for determining the probability of the fire being extinguished. A time limit needs to be established in order to fit in with other ongoing actions during the fire such as "In-house fire fighting". Furthermore if no time limit had been set the node would lose meaning since nearly all smouldering fires eventually turn into flaming ones. Two minutes was chosen as a timeframe in line with typical in-house fire fighting action time. The conditional probability of this node is set according to the state of its parent node "Fire start type" which is also a transfer node from part I of the model.
26. In-house fire fighting effective [states: Yes, No] – This chance node describes the effectiveness or progress made in tackling the fire by the occupant. If the fire is reduced or at least contained then in-house fire fighting can be considered effective. Its conditional probabilities are set according to the state of its parent nodes "In-house fire fighting", "Occupant fire trained", and "Fire fighting equipment"; note "In-house fire fighting effective" can only be positive if "In-house fire fighting"

occurs. The model analyses the effectiveness of having or not having some sort of firefighting equipment, but it does not analyse how effective each individual item of firefighting equipment is. The various types of fire extinguishers, a fire blanket, or a hose will all be effective in different ways, however, data in this detail was not available and hence has not been included the model. Simple tests with hypothetical data within the existing model indicate that having such data would not have had a significant impact on the outcome.

27. Fire extinguished [states: Yes, No] – This chance node represents the event of the fire being put-out. Its conditional probabilities are set in line with its parent nodes "Ventilation", "In-house fire fighting effective", "Fire type 2 minutes after detection", "Fuel load", and "Sprinkler activated"; the latter of these is a transfer node from part I of the model. It should also be noted for smouldering fire situations that if the fire has not been extinguished by this point, that is, through the action of this node, then from here onwards such fires should be considered to have evolved into flaming ones. Another important point is that it is possible for a fire to self extinguish given appropriate conditions such as low fuel combustion and low ventilation, particularly if it is a smouldering fire. "Fire extinguished" also acts as a transfer node into part III of the model.
28. Evacuation successful [states: Yes, No] – This chance node describes the event of the occupant exiting the dwelling unaided; the node therefore influences the probability of rescue being required. The possibility of the occupant being fatally wounded is not considered in this node but rather through a probability within the node "State of the occupant fire stage 1&2". The conditional probabilities of "Evacuation successful" are set according to its parent nodes "Drills", "Full mobility", "Self-evacuation fire stage 1", "Self-evacuation fire stage 2", and "Occupant on ground level". Note that "Evacuation successful" can only be true if either "Self-evacuation fire stage 1" or "Self-evacuation fire stage 2" has taken place. "Drills", "Occupant on ground level" and "Full mobility" will have a positive impact on the probability of this node being true.

29. Rescue required [states: Yes, No] – This chance node represents the situation in which the occupant needs to be rescued or extracted from the dwelling. Its conditional probabilities are set in relation to its parent nodes "Self evacuation fire stage 1", "Self evacuation fire stage 2", "Fire extinguished", "Seek shelter", "Evacuation successful", and "Human reaction", the last of which is a transfer node from part I of the model. The CPT is built on the logic that rescue will be required always except for when evacuation has been successful.
30. Fire growth / flashover [states: Yes, No] – This chance node represents the event of fire growth including flashover occurring. Note that fire can grow rapidly and flashover can occur in as little as two minutes from ignition given the appropriate conditions. Fires which do not grow remain confined to the first item ignited limited by fuel characteristics (availability and flammability) and/or ventilation. The conditional probabilities of this node are set according to its parent nodes "Fire extinguished", "Fuel load", "Ventilation", "Appliance 1 at scene", and "Sprinkler activated" which is a transfer node from part I of the model. Sprinklers are designed to control the development of fires. Their success in suppressing a fire depends upon their reliability in activation and effectiveness in extinguishing the fire. The heat release rate will determine whether the sprinklers activate, thus it is harder for smaller and non-flaming fires to activate sprinkler systems. Sprinklers are designed to control fire development however they will struggle to suppress a fully developed flashover fire. Note that the node "Fire growth / flashover" is also a transfer node feeding into parts III of the model.
31. Smoke spread [states: High, Low] – This chance node represents the extent of smoke distribution throughout the dwelling. Smoke is generally considered more lethal than the fire itself (Communities and Local Government, 2011b; Yung 2008; Perry, 2003; Thomson, 2002; Stollard and Abrahams, 1999; Babrauskas *et al.*, 1998) so incorporating the influence of smoke within the model is important. Quantifying the degree of smoke spread within a property is a complex task and would require modelling various parameters as described in Chapter 2 (section 2.2.1.1). Attempting to incorporate such modelling in the BN would only be appropriate if the BN was

used to study a single dwelling. Since this is not the case the linguistic terms "High" and "Low" are used for this node. Within the BN a high smoke spread scenario occurs when i) more than 50% of the fire room of origin is enveloped by dense smoke through which human vision is totally obstructed, and; ii) smoke has begun to spread to other parts of the dwelling. This node's conditional probabilities are set according to its parent nodes "Fire extinguished", "Fuel load", "Ventilation", and "Fire growth / flashover".

32. Smoke lethality [states: High, Low] – This chance node describes how lethal the dwelling fire smoke is to humans. An account of smoke and toxic fumes is provided in Chapter 2, section 2.2.1.1. It is worth noting that in recent years the amount of plastics and other materials that emit toxic fumes when burnt has increased in homes and society as a whole. This node is important because of the high impact it has on the probability of an occupant surviving a fire. Its conditional probabilities are set in line with its parent nodes "Smoke spread" and "Fuel toxicity". The node is also a transfer node linking part II to part III of the model.
33. Rescue completed fire stage 1&2 [states: Yes, No] – This chance node represents the action of the occupant being rescued while the fire is still ongoing. The term "completed" refers to the accomplishment of physical extraction of the occupant rather than their state of health at the time; hence an uncompleted rescue means that the occupant remains trapped in the dwelling rather than being dead. The condition of being alive or dead is captured through the node "State of occupant fire stage 1&2" (described below). This includes a rescued person that may have already lost their life within the dwelling or who may lose their life over the next 15 minutes. The conditional probabilities of the node "Rescue completed fire stage 1&2" are set in line with its parent nodes "Rescue required", "Occupant on ground level", "Appliance 1 at scene", and "Passerby intervention".
34. State of occupant fire stage 1&2 [states: Alive – well / minor injury, Alive – major injury, Dead, Trapped / Unknown] – This chance node describes the living status of the occupant and whether he/she is trapped or not in the dwelling. There are four states for this node: the first state [Alive – well / minor injury] entails either no

injury or a relatively small injury such as broken bones, cuts, bruises, trauma, shock, and other conditions from which a person would normally fully recover; the second state [Alive – major injury] involves damage such as a broken back, long term scarring / burns, life threatening injuries, and other conditions from which a person may never fully recover; the third state [Dead] signifies that the occupant has lost their life; the fourth state [Trapped / Unknown] means that the occupant is still within the dwelling and that his/her state or condition may or may not be known. Note that sometimes people with major injuries for example fractured skull, internal bleeding, heart failure, poisoning from smoke, *etc.*, lose their life shortly after being rescued or escaping from an unsafe situation, therefore this node "State of occupant" considers the condition of an occupant up to 15 minutes after rescue or escape has occurred. After this period other factors become more influential such as intervention from ambulance and medical teams. This node's conditional probabilities are set in accordance with the state of its parent nodes "Self evacuation fire stage 2", "Rescue required", Rescue completed fire stage 1&2", and "Smoke lethality". The node being described here is of particular importance because it serves as a means of measuring the degree of human safety of a particular fire situation and hence could be used as an input for risk quantification purposes at a later stage of analysis. This node is also a transfer node from part II feeding into part III of the model.

There are two versions of part II of the model, the first is the 'risk-map' linked version, the second the "Fire time response module" (or part IV) linked version. The 'risk-map' linked version functions independently from part IV of the model with FRS response time based upon the level of risk assigned through MFRS's risk map. The 'risk-map' linked version which is the one being dealt with in this chapter is presented in Figure 5.2. The nodes have been set out with events flowing from top to bottom where possible.

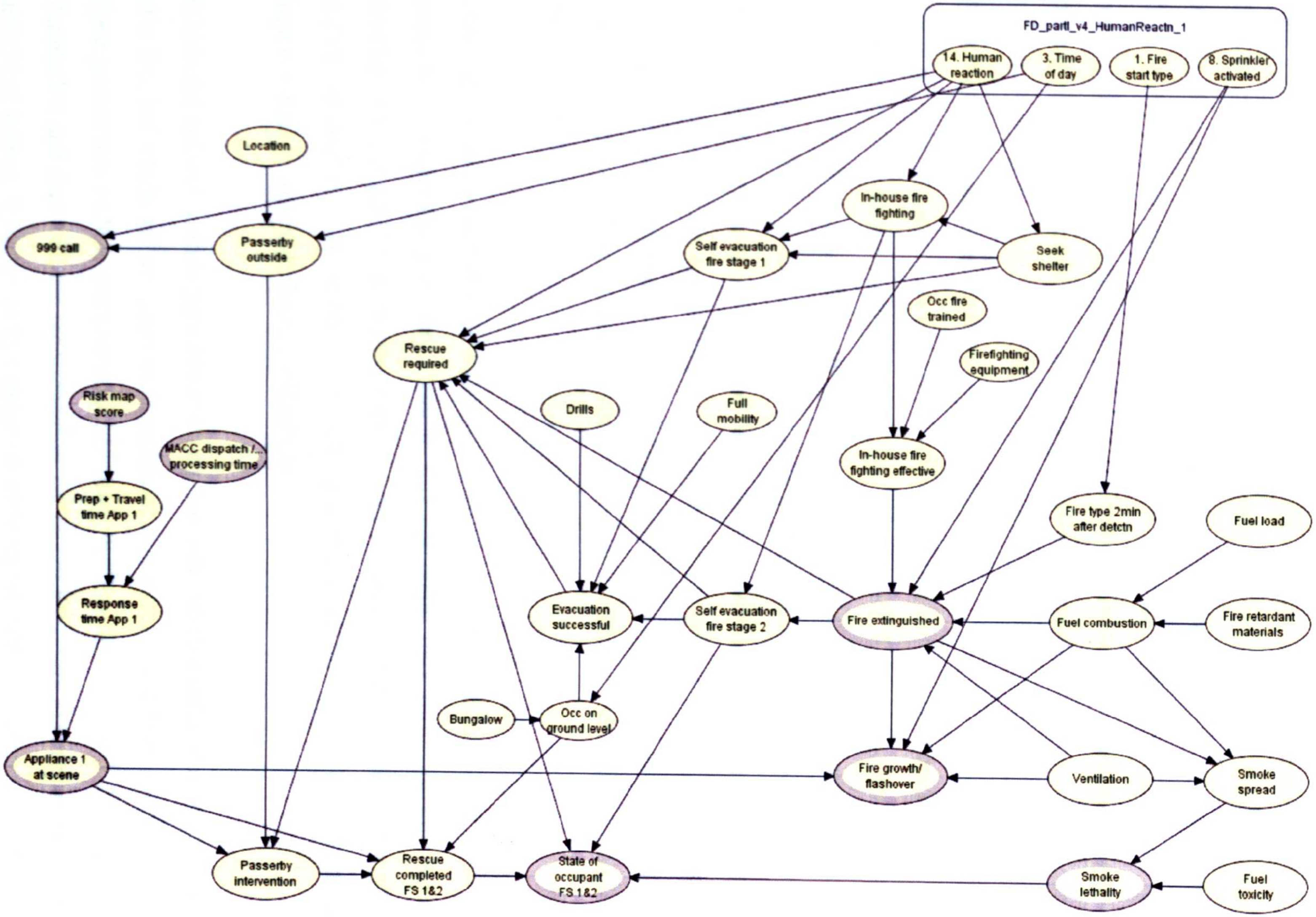


Figure 5.2. BN Model Part II ('risk-map' linked version) representing occupant response and further fire development.

In the network (Figure 5.2), nodes which are of similar theme or which are connected have been kept as close as possible to each other. For example FRS response nodes are placed close to each other towards the left of the network; fuel combustion and smoke nodes have been located in close proximity on the bottom right of the network. The four transfer nodes from part I of the model are located towards the top right of the network within a rectangular box; these nodes are described in Chapter 4. Nodes which are shaded grey round the edges are transfer nodes from part II to part III of the model.

5.2.4 Note on parameters excluded from the network

There are various parameters that play a role in defining the development of a fire within a compartment; these parameters are fuel type, fuel load, fuel arrangement, compartment geometry, ventilation, ignition location, ignition source, among others. Within certain building types the occurrence of some of these parameters cannot be determined for fire risk assessment purposes. An example of this would be ventilation within dwellings, where windows and doors are opened based on random human behaviour, and the influx of wind on weather conditions; in contrast ventilation within many public buildings is deterministic since it is controlled by ventilation systems regulating the inflow and outflow of air between each compartment.

There are other parameters over which statistically significant data cannot be collected, for example compartment geometry. Though this parameter may influence the way a fire develops it is not possible to represent the geometry characteristics statistically for all rooms and for all dwellings. However, this may be possible for certain types of buildings such as high rise flats in which all floors are identical.

Within the network certain parameters which may have an influence upon the development of a fire, but which are not possible to represent statistically have been excluded. Some of these parameters include compartment geometry, ignition location, and fuel arrangement. Ventilation and fuel load are represented in the model for future experimental purposes of individual homes, however at this point no meaningful data is available to represent the housing stock; it is thus assumed within the model that these parameters are uniform across dwellings and hence have a 50/50 probability.

5.2.5 Model d-separation

D-separation has been defined in section 4.2.4. There are two focus nodes for part II of the model "State of the occupant fire stage 1&2" and "Fire growth / flashover". In similar fashion to part I of the model, a d-separation test has been undertaken using Hugin to demonstrate that the model has been simplified and that there are no superfluous nodes. Figure 5.3 shows d-separation with focus node set on "State of the occupant fire stage 1&2", the nodes which are *d-separated* (relevant) have a tick, and those which are *d-connected* (irrelevant) have a cross, in this case none. Note that the transfer (instance) nodes from part I of the network have been deleted, otherwise d-separation cannot be performed with Hugin.

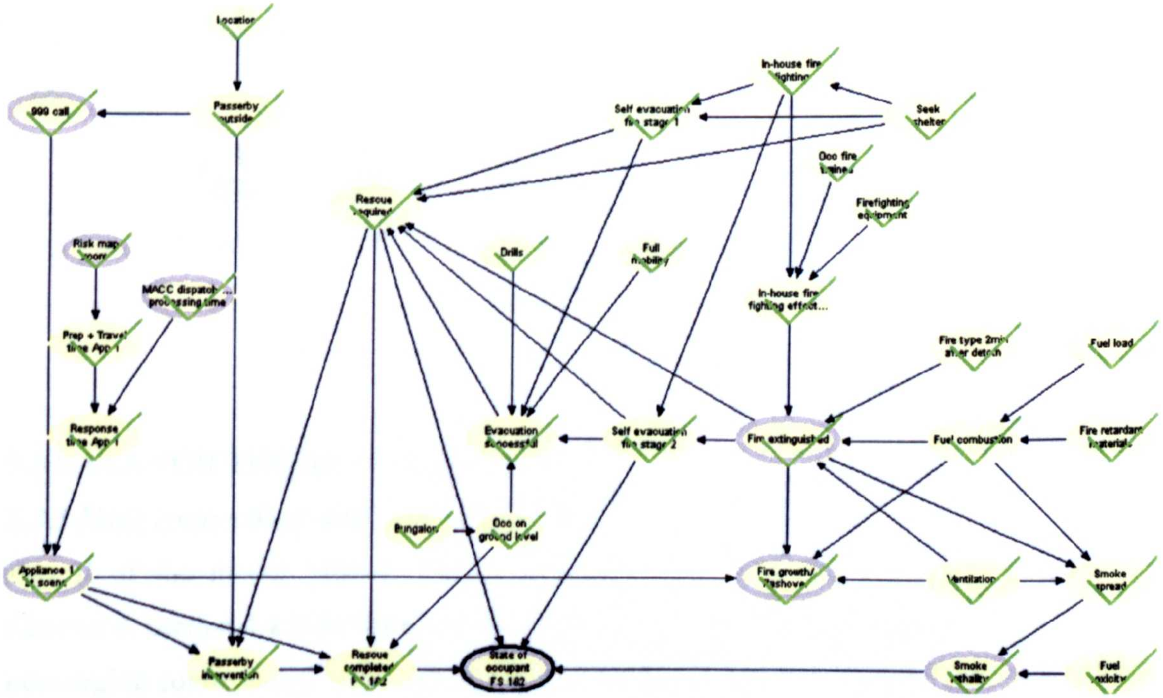


Figure 5.3. BN Model Part II showing d-separation for the focus node "State of the occupant fire stage 1&2".

Figure 5.4 gives d-separation for the other focus node "Fire growth / flashover". In this case four nodes are *d*-connected or irrelevant however they must be kept since they are relevant to the other focus node and hence the rest of the model. Further d-separation checks have been conducted for other nodes throughout the network to ensure relevance of respective influencing nodes.

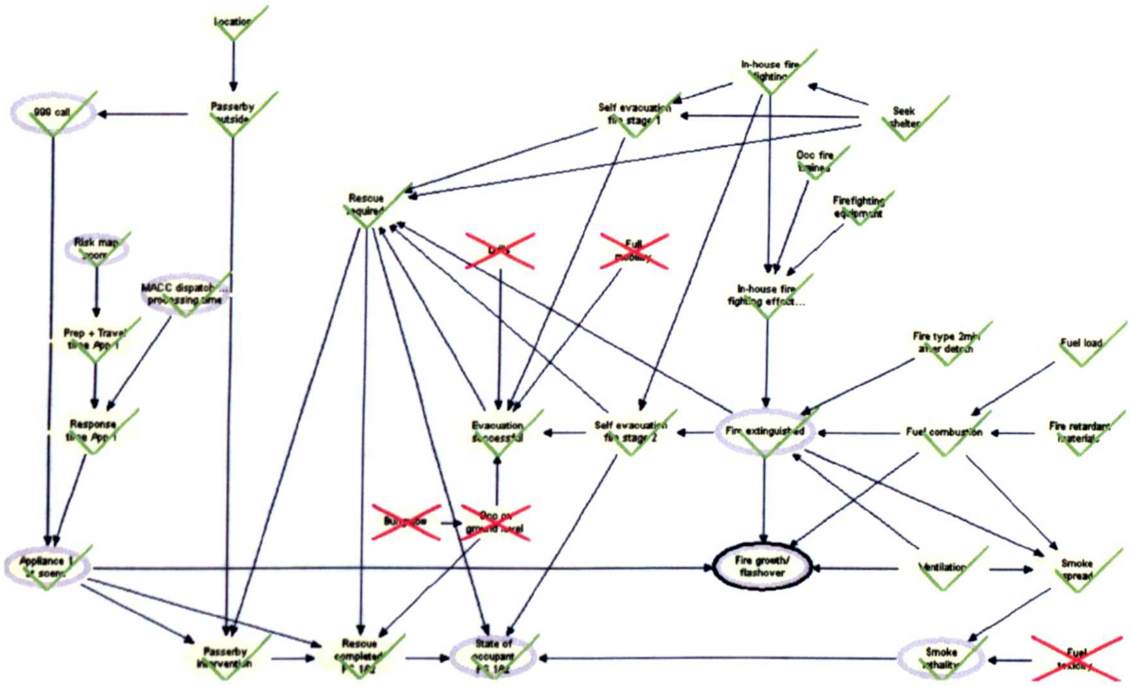


Figure 5.4. BN Model Part II showing d-separation for the focus node "Fire growth / flashover".

5.3 DATA FOR THE BN MODEL – PART II

5.3.1 Node connections and construction of CPTs

Part II of the model features serial, diverging, and converging node connections (see Chapter 4, section 4.2.4 for the theoretical background). There are two nodes with quadruple converging connections, three with quintuple converging connections and one with sextuple converging connections. There are also several nodes which diverge into multiple child nodes. Constructing CPTs for this part of the model was challenging since virtually none of the data existed in the required form. The particular combination of factors set forth in the network had as a whole never been modelled this way. Although research exists on some of the aspects of the model, for example the spread of smoke during a fire, the rate of growth of a fire, the behaviour of people when faced with life threatening situations, *etc.*, the manner in which they relate to each other had to be deciphered and the most applicable information extracted. Often the information was not entirely applicable and had to be treated to fit the model. Constructing data to model the effect of certain combinations of parent nodes upon a child was undertaken using a variety of techniques and applying a series of assumptions based on expert knowledge. Appendix 8 details how some of the more complex Chapter 5 CPTs were constructed and Appendix 9 provides all the tables.

5.3.2 Summary of node data content

Node data was compiled using a combination of statistics and knowledge about a parameter. Expert opinion was used to complete data for many nodes; the process is described in Chapter 4, section 4.5. Subjective estimates were also applied by the author based on personal communication with experts, and from reviewing academic and industrial information. Table 5.1 summarizes the origins of data for each node of part II of the model along with the number of states, parent nodes, and permutations for each probability table. Specific sources of literature are not named in the table but are included within the text where relevant. For example the CPT for node 1 has been completed from the English Housing Survey (Communities and Local Government, 2010c), nodes 2 and 3 from Marriott (2003) and Reynolds (2002), node 5 from Yung (2008) and Stollard and Abrahams (1999), *etc.* The nodes in Table 5.1 are separated by theme or aspect of the network. As with part I of the model, many of the nodes have a subjective element within their probability; the degree of subjectivity varies between parameters. In some cases it was relatively uncomplicated to compile the information, for example in the case of the root node "Firefighting equipment". Although hard statistics did not exist, a report from Reynolds (2002) was used along with expert opinion to compile the data. Compilation of data for many non-root nodes was not as straight forward and has been discussed where relevant.

Note that the nodes "Fuel load" and "Ventilation" in the table are annotated as probabilities unavailable; this is explained in section 5.2.3 which described the nodes.

Table 5.1. Probability table details for each node and origins of data for part II.

Node #	Node name	# of states	# of parent nodes	# of permu-tations in prob. table	Probabilities compiled from	Subjec-tive element
Transfer nodes from part I of the mode.						
1	Fire start type	2	0	2	Exp. op., literature	Yes
3	Time of day	2	0	2	Literature	Yes
8	Sprinkler activated	2	2	4	Literature	Yes
14	Human reaction	2	4	32	Exp. op., literature	Yes
Part II: Pre-conditions						
1	Location	3	0	3	Literature	No
2	Occupant fire trained	2	0	2	Literature	No
3	Firefighting equipment	2	0	2	Literature	Yes
4	Fuel load	2	0	2	unavailable (50/50)	n/a
5	Fire retardant materials	2	0	2	Exp. op., literature	Yes
6	Fuel combustion	2	2	8	Exp. op., literature	Yes
7	Drills	2	0	2	Exp. op., literature	Yes
8	Full mobility	2	0	2	Exp. op., literature	Yes
9	Ventilation	2	0	2	unavailable (50/50)	n/a
10	Fuel toxicity	2	0	2	Exp. op., literature	Yes
11	Bungalow	2	0	2	Literature	No
12	Risk map score	3	0	3	Literature	No
Part II: Human actions						
13	Occupant on ground level	2	1	4	Exp. op., literature	Yes
14	999 call	3	2	12	Exp. op., literature	Yes
15	Seek shelter	2	1	4	Expert opinion	Yes
16	In-house fire fighting	2	2	8	Exp. op., literature	Yes
17	Self evacuation fire stage 1	2	3	16	Exp. op., literature	Yes
18	Self evacuation fire stage 2	2	2	4	Exp. op., literature	Yes
19	Passerby intervention	2	2	24	Exp. op., literature	Yes
Part II: FRS interaction						
20	MACC dispatch / call prcess. T	3	0	3	Questnnr., exp. op.	Yes
21	Prep. + travel time app. 1	3	1	9	MFRS resp. stand.	No
22	Response time appliance 1	3	2	27	MFRS, see App 7	No
23	Appliance 1 at scene	3	2	27	MFRS, see App 7	No

			Part II: Occurrences / fire development			
24	Passerby outside	2	2	12	Exp. op., literature	Yes
25	Fire type 2 mins. after detect.	2	1	4	Exp. op., literature	Yes
26	In-house fire fighting effective	2	3	16	Literature	No
27	Fire extinguished	2	5	64	Exp. op., literature	Yes
28	Evacuation successful	2	5	64	Exp. op., literature	Yes
29	Rescue required	2	6	128	Event logic	No
30	Fire growth / flashover	2	5	96	Exp. op., literature	Yes
31	Smoke spread	2	2	8	Exp. op., literature	Yes
32	Smoke lethality	2	2	8	Exp. op., literature	Yes
33	Rescue completed	2	4	48	Exp. op., literature	Yes
34	State of the occupant FS 1&2	4	4	64	Exp. op., literature	Yes

5.4 PRIOR PROBABILITY CALIBRATION

Once part II of the model was complete the nodes with complex CPTs deemed to be of prime importance, as well as other important nodes, were checked against existing statistics to ensure they represented reality. Important nodes were either those producing directly applicable results, for example "State of the occupant FS 1&2", and those key or central within the network, for example "Fire extinguished". An example of a node with a complex CPT is "Response time appliance 1" which is included in the check. The model was compiled in Hugin and prior probabilities compared to real data; note that in Hugin probabilities are expressed out of 100 and this is maintained in the text. The following nodes were checked:

- Fire growth / flashover: Prior probabilities were [Yes: 56.99, No: 43.01]. These values were compared with UK fire spread statistics from Stollard and Abrahams (1999). Fire was confined to the first item ignited, hence there was no fire growth, in 43% of dwelling fires; this is very close to the prior probability.

- Fire extinguished: Prior probabilities were [Yes: 19.30, No: 80.70]. These values were discussed with experts at MFRS who agreed that fires were probably extinguished by the occupant on 20% of occasions.

- Preparation + travel time appliance 1: Prior probabilities were [<5m: 71.72, 5 to 10m: 25.50, >10m: 2.78]. These values were compared with data from Communities and Local Government (2009). The statistics present appliance response times (excluding call handling time) across regions in England between 1996 and 2006. The North West had a mean response time oscillating between 4.9 and 6 minutes. The mean value over the period was 5.5 with a median of 5.7. These values appear slightly above the prior probabilities for this node however two points could explain the difference: firstly the data is for the whole of the North West region, whilst this model has been set with data for Merseyside; secondly there has been a decrease in travel time over the last couple of years indicating that the present crew preparation and travel times may be much closer to the prior probabilities of this node.

- Response time appliance 1: Prior probabilities were [<5m: 60.84, 5 to 10m: 32.51, >10m: 6.65]. These probabilities were compared with data from Holborn (2004) who presents statistics for time intervals for the London Fire Brigade. Time from call to the arrival of the fire brigade had a mean value of 4.6 minutes and a median of 4. This appears to match closely the prior probabilities but it must be noted that the data set is for a different region of the country.

- State of the occupant fire stage 1&2: Prior probabilities were [Alive – well / minor injury: 76.73, Alive – major injury: 10.42, Dead: 0.20, Trapped / Unknown: 12.64]. No data was found with which to compare these values; however statistics from Communities and Local Government on the number of dwelling fires and dwelling fire fatalities for the UK was available on a yearly basis; this data has been reviewed in Chapter 2, section 2.4.4. From these two data sets it is possible to work out the probability of a fatality at a dwelling fire. This has been computed between the years 1996 and 2010 giving a range between 0.63 and 0.78 with an average of 0.70 and a median of 0.69. The prior probability of "State of the occupant fire stage 3" presented in Chapter 6 is 0.72 for fatality which is reasonably close to the data derived from Communities and Local Government. The difference may be explained by the model being representative of Merseyside whilst the government data sets of the UK; furthermore it has been noted in Chapter 2, section 2.5 that Merseyside has a higher fatality rate than most of the rest of the country which would account for the higher prior probability for fatality.

Table 5.2 provides a summary of prior probabilities of the nodes which were checked, as described above. Columns 4 and 5 contain the statistics that they were compared against.

Table 5.2. Summary of nodes that were checked for consistency of prior probabilities with 'real world' statistics (note probabilities are expressed out of 100).

Node	Prior probability state	Prior probability for state	Statistic region and period:	Statistic
Fire growth / flashover	No	43.01	UK, 1992*	43.00
Fire extinguished	Yes	19.30	UK, recent years*	20.00
Prep + travel time App 1	<5m	71.72	Merseyside, 1996-2006*	mean 5.5m
Response time App 1	<5m	60.84	London, 2004*	mean 4.6m
State of occupant FS3	Dead	0.72	UK, 1996-2010*	0.70

* References for this data are provided in the text within section 5.4.

5.5 MODEL PART II CASE STUDIES

As demonstrated in part I of the model (Chapter 4, section 4.7) case studies are useful for showing how the research can be put into practice. Part II of the model is now used to study a series of possible real world scenarios. All variables from part I of the model remain unchanged unless otherwise stated and only those directly involved in the study from part II are altered through the *run mode* of Hugin. Posterior probability distributions are computed for likelihood diagnosis of nodes of interest given particular evidence. The focus of part II of the model is on fire growth, evacuation, rescue, and occupant wellbeing given specific actions by the occupant, performance by FRS's, and dwelling characteristics. Occupant specific actions might include firefighting, escape, or seeking shelter; FRS performance covers various factors involved in response time; dwelling characteristics includes factors regarding fuel, elevation of the property, firefighting equipment, sprinklers, and so forth. It is worth noting that the model could be used for generating a high number of results. It is thus important to carefully select the factors to be analysed so that the most relevant and useful results are generated. In this instance the case studies formulated are geared towards analysing how numerous variables affect some of the principal outputs of this part of the model, namely the probabilities of fire growth, fatality and remaining trapped. The effect of the perceived most influential variables are combined and compared. For example, case 1 analyses how FRS response time and occupant actions affect the probability of remaining trapped. These factors have been documented to have a high impact upon the probability of the survival; in the case of response times refer to Fire Brigades Union (2012), Communities and Local Government (2009), and Mattsson and Juas (1997), while for occupant actions see Thompson (2011) and Meacham (1999). The model allows for a comparison of the combined effects of various occupant actions and different FRS response times to be made, which are presented within the results. In other case studies the effect of different safety configurations and common fire scenarios are compared. Each case study explains the interest in developing its respective results. The following five cases studies are now presented:

Case 1 – 999 call, FRS response time, and occupant actions, effect upon escape

Test 1.1: The survival of an occupant during a dwelling fire depends on various factors. In this case study the time taken to make an emergency 999 call is analyzed in conjunction with actions undertaken by the dwelling occupant. The effect upon the likelihood of remaining trapped, captured within the node "State of the occupant fire stage 1&2", is examined. Results are presented by means of a bar chart (Figure 5.5) which shows the probability of remaining trapped in the dwelling (y-axis) following arrival of FRS's and assuming the fire does not self extinguish. This is dependent upon the mutually exclusive actions taken by the occupant (x-axis), and the time taken to make an emergency 999 call. Time is continuous by nature but within Hugin a continuous node cannot be a parent of a discrete chance node (see section 5.2.1). The "999 call" node has been implemented as a discrete node with three states: less than 1 minute, 1 to 3 minutes, and over 3 minutes (see bar chart colour legend).

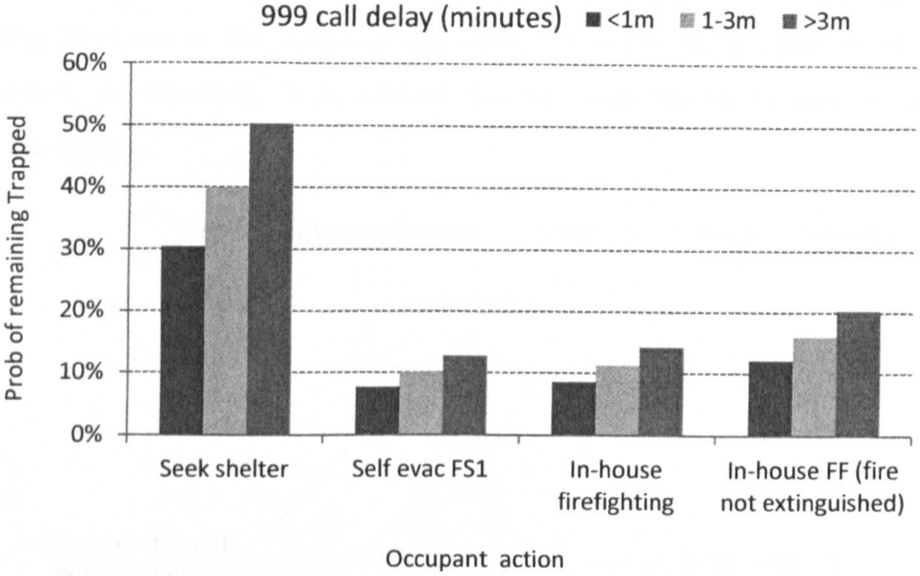


Figure 5.5. Effect of 999 call delay on posterior probabilities of the node "State of the occupant fire stage 1&2" [state: Trapped / Unknown], with evidence inserted for "Seek shelter", "Self evacuation fire stage 1", "In-house fire fighting", and "Fire extinguished".

From the results it is evident that the worse course of action a person could take in terms of remaining trapped within the dwelling, would be to seek shelter. Conversely the best decision a person could make is to evacuate. In many cases however, a person will choose to remain in the dwelling to attack the fire. According to the model such an action would increase the probability of becoming trapped although by a minimum amount. Nonetheless if evidence is inserted confirming that the fire was not extinguished then the probability of remaining trapped increases noticeably. Within all situations this is made worse the longer it takes to call the emergency 999 number. The probability of remaining trapped almost doubles (increases by roughly x 1.7) between situations where the occupant calls 999 within 1 minute and after 3 minutes. This case study demonstrates the importance of educating people regarding what they should do in the event of a dwelling fire; even though each fire event is unique it is vital that a person makes an immediate 999 call and leaves the dwelling rather than engaging in any other activity. Figure 5.6 presents a radar chart which highlights further the differences between the courses of action undertaken by an occupant. The closer the gyrating lines are to the centre of the chart the lower the probability of remaining trapped within the dwelling. It is evident that the seek shelter is furthest away by a considerable distance.

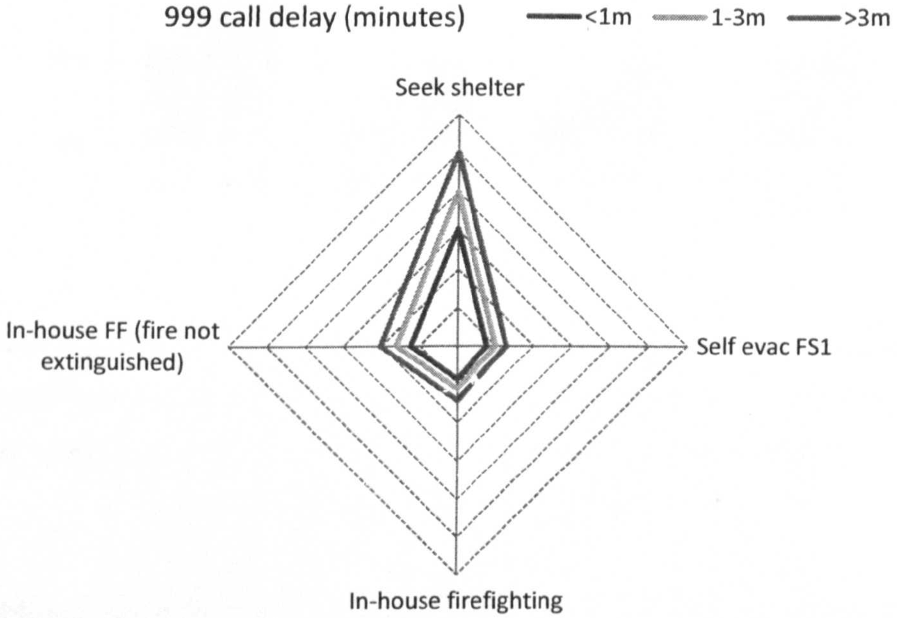


Figure 5.6. Radar chart of effect of 999 call delay on posterior probabilities of the node "State of the occupant fire stage 1&2" [state: Trapped / Unknown], with evidence inserted for "Seek shelter", "Self evacuation fire stage 1", "In-house fire fighting", and "Fire extinguished".

Test 1.2: A test similar to *test 1.2* was conducted replacing 999 call with FRS crew preparation and travel time to assess the difference between the two upon the likelihood of remaining trapped in the dwelling. Results are presented again through a bar chart (Figure 5.7) which shows the probability of remaining trapped in the dwelling following arrival of FRS's (y-axis). Different occupant actions are once again examined but on this occasion with a different time node: "Preparation + travel time" states [<5m, 5 to 10m, >10m].

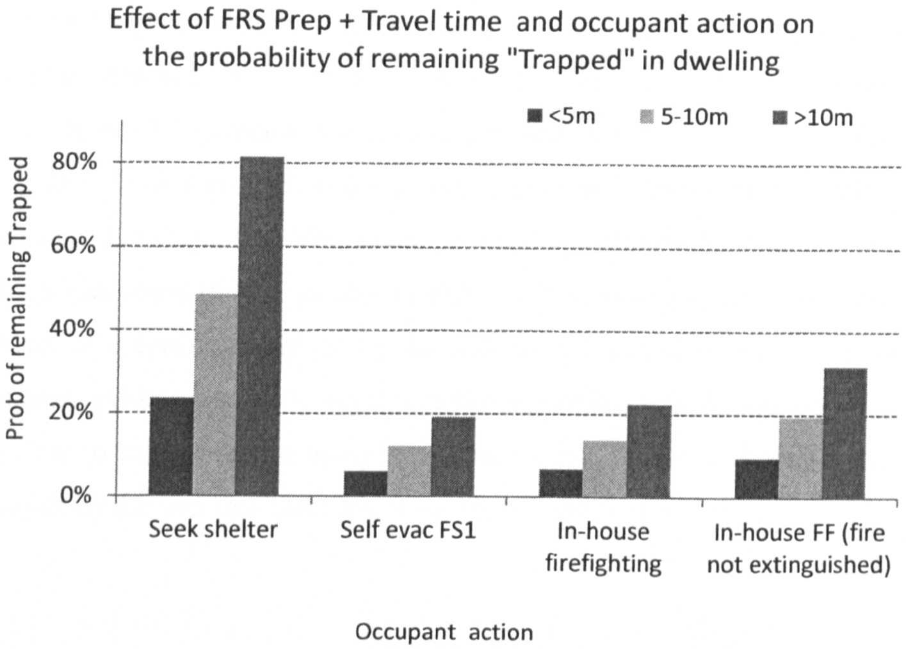


Figure 5.7. Effect of FRS preparation + travel time of appliance 1 upon posterior probabilities of the node "State of the occupant fire stage 1&2" [state: Trapped / Unknown], with evidence inserted for "Seek shelter", "Self evacuation fire stage1", "In-house fire fighting", and "Fire extinguished".

It was established in *test 1.1* that the best and worst actions a person could undertake were to evacuate and seek shelter respectively; this again is reflected in Figure 5.7. The impact of FRS preparation and travel time upon remaining trapped is however far more significant than 999 call time. The difference in the probability of remaining trapped with the FRS's arriving within 5 minutes from the moment of dispatch to arriving after 10 minutes is more than treble (increases between x 3.2 and 3.5). This test demonstrates the importance of prompt FRS arrival at a dwelling fire incident. Any increase in the travel time of FRS can have a big impact upon the chance of being rescued or remaining trapped in a fire.

Case 2 – Location and risk level effect upon escape and survival

MFRS set their response standards based upon the level of risk assigned to each LSOA as explained in Chapter 2, section 2.4.4. This test investigates how the level of risk assigned actually affects the probability of death or remaining trapped in dwelling fires. The analysis also cross examines how the location / urbanization category of the dwelling affects this probability. Figure 5.8 presents the results grouped along the x-axis by risk map level (FRAM). It is evident that high risk dwellings command lower probabilities of death or remaining trapped during a fire. This lower probability during a fire is however offset by the fact that high risk areas have a greater number of fire incidents per year. The variation in terms of level of urbanization, given by the different shades of colour on the graph, is that more rural areas possess a slightly higher probability of death or remaining trapped during a fire; this is due to help or rescue being less at hand. This higher probability during a fire is however offset by the fact that there are fewer dwellings in rural areas.

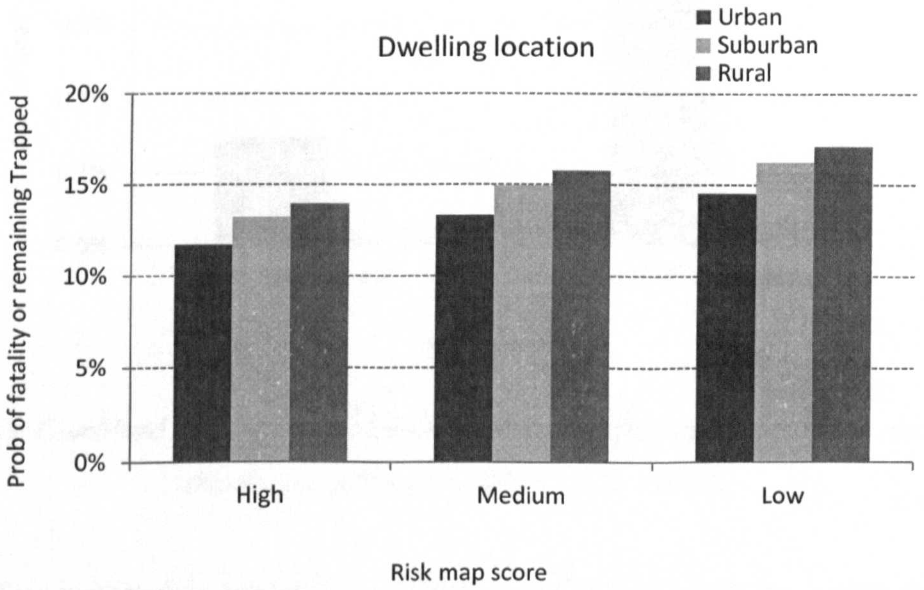


Figure 5.8. Effect of dwelling location and risk map score upon posterior probabilities of the node "State of the occupant fire stage 1&2" [state: Dead, Trapped / Unknown].

Case 3 – Smoke lethality and occupant action effect upon probability of fatality

The lethal effect of smoke has been highlighted earlier in this research, but how does this combine with the action an occupant might take during a fire? In this test the combined impact of smoke lethality and occupant action upon the probability of fatality is examined.

Figure 5.9 presents the results through a bar chart. The probability of fatality at this stage of the fire is still relatively low however there is a huge difference between the probabilities when smoke lethality is high. If the occupant decides to remain in the property to fight the fire their chance of death is almost three times higher. The point to note here is that it is even more perilous to attempt to fight a fire in situations where smoke lethality is high compared to situations where it is low.

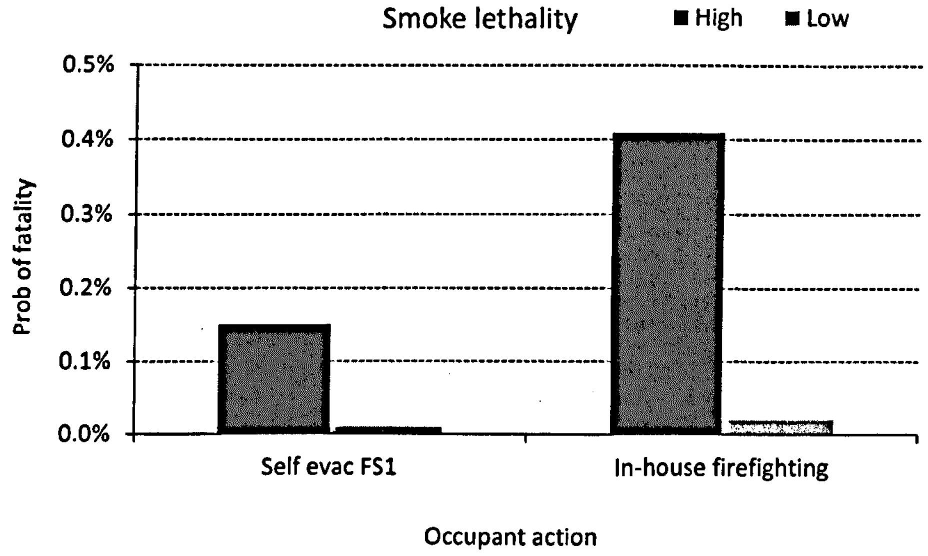


Figure 5.9. Combined effect of smoke lethality and occupant action upon the node "State of the occupant fire stage 1&2" [state: Dead].

Case 4 – Fuel combustion, ventilation, and FRS response effect upon fire growth/flashover

Several studies and experience from the fire services indicate that dwelling fires today develop faster than 30 years ago (Hofman *et al.*, 2007); this is probably because of the increased usage of plastics and textiles in homes. Flashover is commonly reached within four to ten minutes but in extreme cases in as little as one to two minutes. The importance of fuel combustion and prompt arrival of FRS's is paramount in determining the growth of a fire. This test now looks at the effect of these two parameters upon the probability of fire growth / flashover. The results are provided in Figure 5.10 with the probability given along the y-axis. The x-axis describes the parameters being evaluated; the effect of ventilation has also been considered although there is no statistically significant marginal probability data for this node as mentioned in node description in section 5.2.3, thus this parameter is included just out of interest. It is evident from the graph that higher fuel combustion results in greater fire growth, the difference between high and low combustion rates varying between 1.4 and 1.2 times greater for the former. This however can be limited by the prompt arrival of FRS's, particularly if they arrive within 5 minutes when the fire is in its early stage. The difference between response times of 5 to 10 minutes and greater than 10 minutes is less significant implying that the fire has probably taken hold by then. In conditions of higher ventilation fire growth / flashover probabilities are higher in all cases; data however needs to be obtained to verify the degree of influence more precisely.

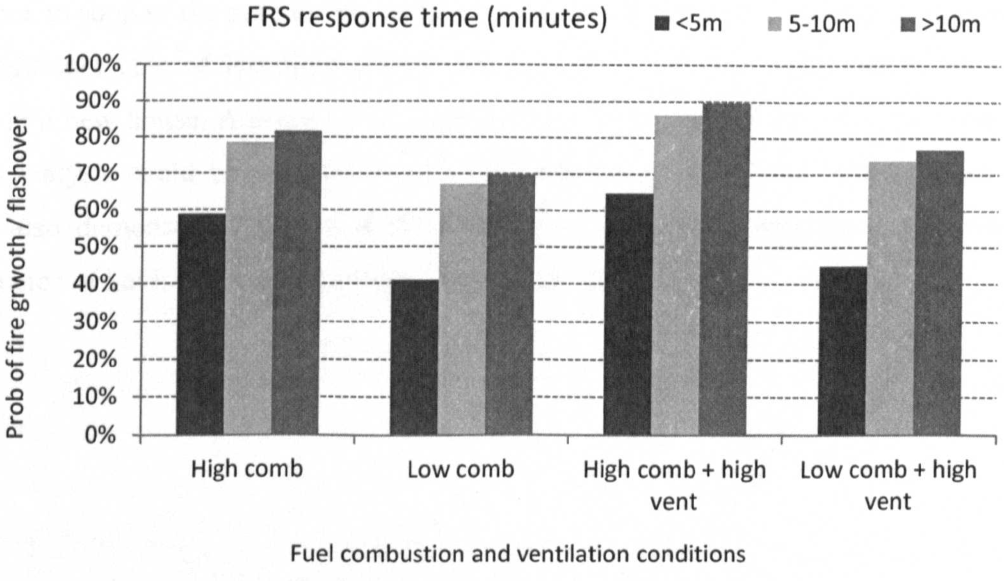


Figure 5.10. Combined effect of fuel combustion, ventilation, and FRS response time upon the posterior probability of the node "Fire growth / flashover" [state: Yes].

Case 5 – Smoke alarm sound, sprinkler activation, and time of day effect upon fatality or remaining trapped

The effect upon survival of a dwelling fire during fire stages 1 and 2, that is whilst the fire is small to medium size (see section 5.2.2), is examined as a combined function of smoke alarm sounding, sprinkler being activated, and time of day. These three parameters are all nodes from part I of the model. The test demonstrates how part I and part II of the model work together; results are provided in Figure 5.11. The y-axis shows the probability of either death or remaining trapped in the dwelling fire. The front row of bars shows the probabilities for daytime situations and the rear row for nighttime situations (z-axis). The x-axis provides the smoke alarm and sprinkler conditions during the fire. The results show how effective a sprinkler can be in reducing the probabilities of death or remaining trapped in a fire, considerably more so than a smoke alarm; the latter provides only a warning however the former provides both a warning and a firefighting option. This can be used as evidence to support the case for the installation of sprinklers in new homes. It is argued that the additional cost of installing a sprinkler system is minimal compared to the cost of building a new house. A cost-benefit analysis would however be required; the benefit part of the analysis could be provided from case studies such as the one presented here. The graph also demonstrates how nighttime situations are more dangerous highlighting the importance of having at least a smoke alarm in a dwelling.

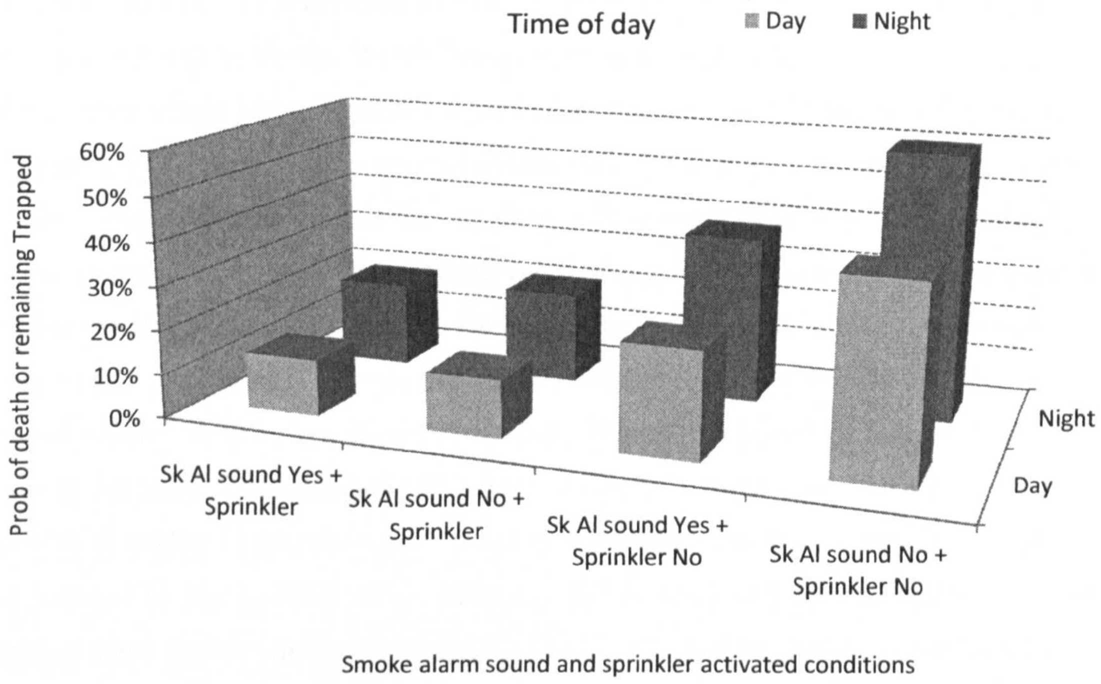


Figure 5.11. Combined time of day, smoke alarm sound, and sprinkle activation upon the posterior probability of the node "State of the occupant fire stage 1&2" [state: Dead and Trapped / Unknown].

5.6 SENSITIVITY ANALYSIS

The fundamentals and reasons for undertaking SA are discussed in Chapter 4, section 4.8. Essentially sensitivity analysis in this context is a measure of dependence between selected input nodes and the output of a network. Knowing which nodes are the most influential can assist in experimentation, analysis, and further research with the model; nodes which are not important can be identified and if necessary discarded or replaced.

SA was conducted for part II of the model examining the sensitivity upon the two focus nodes. The first focus node "State of the occupant fire stage 1&2" was tested to changes in the root nodes "Drill", "Full mobility", "Bungalow", "Fire retardant materials", and "Fuel toxicity. Tests were conducted in Hugin using the parameter sensitivity wizard; manual calculations have been undertaken in Chapter 4, section 4.8 to check that the process was being conducted correctly. Within Hugin each input node was paired individually with the focus node which had to be set to a particular state. In this case the sensitivity to the states [Dead] and [Trapped / Unknown] was examined; note that there are four states for this focus node. A state for each input node was purposely selected to have a positive value upon the focus node; in other words an absolute value of sensitivity was taken to make comparisons easier to view. Figure 5.12 presents the results for the focus node "State of the occupant fire stage 1&2" state [Dead]. All the root nodes tested are far away within the network from the focus which is why values are relatively low. The most sensitive of these is "Full mobility" whilst the least "Fire retardant materials". Table 5.3 summarizes the sensitivity values of occupant fatality to the root nodes. It can be concluded that the probability of death is most influenced by the mobility of an individual followed closely by fuel toxicity. It stands to reason that a person who is not mobile will have a far smaller chance of escaping a fire.

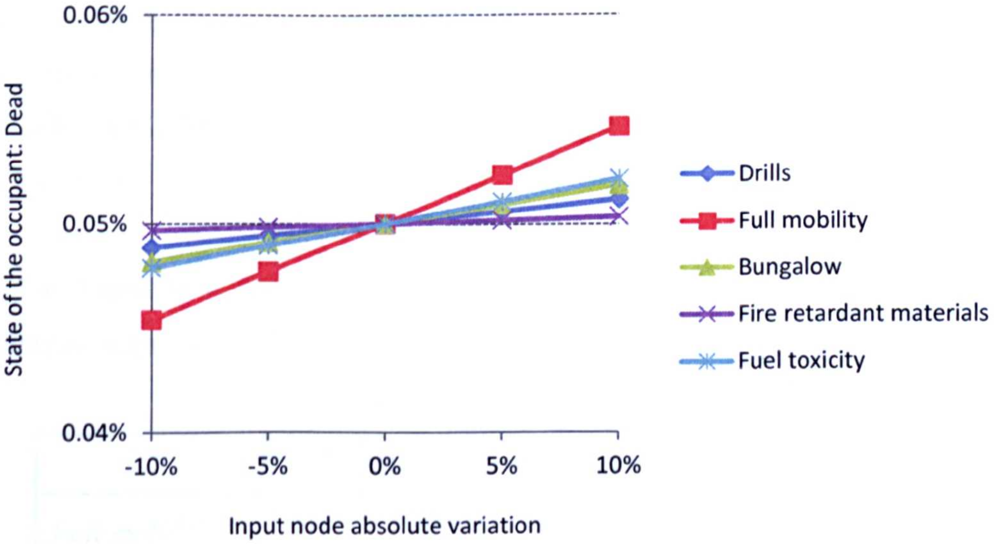


Figure 5.12. Sensitivity functions of five root nodes on "State of the occupant FS 1&2".

Table 5.3. Sensitivity values for five input nodes acting upon the output node "State of the occupant fire stage 1&2" state [Dead]. Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Fuel mobility	0.000467
Fuel toxicity	0.000215
Bungalow	0.000187
Drills	0.000119
Fire retardant materials	0.000034

The sensitivity values to "State of the occupant fire stage 1&2" state [Trapped / Unknown] are presented in Table 5.4. Again the most influential node is "Full mobility" which seems logical since a person would need to be mobile in order to escape from a fire. The second node in the table is "Bungalow" which determines the number of floors a dwelling has. Since it is easier to escape from the ground floor it makes sense that this node is one of the most significant in terms of escape. At the bottom of the table is "Fuel toxicity". This parameter has a big impact upon survival, but in terms of escape it is negligible as can be seen in Table 5.4.

Table 5.4. Sensitivity values for five input nodes acting upon the output node "State of the occupant fire stage 1&2" state [Trapped / Unknown]. Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Full mobility	0.04
Bungalow	0.02
Drills	0.01
Fire retardant materials	0.000167
Fuel toxicity	5.71E-18

The sensitivity of the second focus node "Fire growth / flashover" was examined next. This time the effect of six nodes (root and non-root) were compared. Results are presented in Figure 5.13 and Table 5.5. In this case the sensitivity values are much higher with FRS "Preparation + travel time" being the most influential node followed by "999 call"; the least influential node was "Occupant fire trained". It can therefore be deduced that the prompt arrival of FRS's is more important in terms of determining fire growth than any potential firefighting action by the occupant.

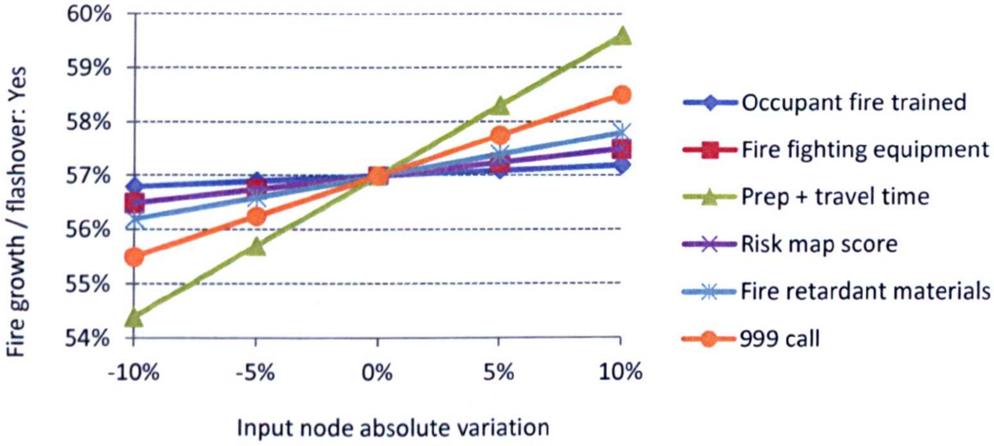


Figure 5.13. Sensitivity functions of six nodes on "Fire growth / flashover".

Table 5.5. Sensitivity values for six input nodes acting upon the output node "Fire growth / flashover". Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Prep + travel time	0.26
999 call	0.15
Fire retardant materials	0.08
Firefighting equipment	0.05
Risk map score	0.05
Occupant fire trained	0.02

5.7 FURTHER DEVELOPMENTS OF PART II OF THE MODEL

One of the benefits of the BN technique is that the network can continue to be built as more knowledge is gathered about a system or if new aspects have to be analysed. In similar fashion to part I of the model, part II can be expanded to include some social aspect which would impact the actions of an occupant. In Chapter 4, section 4.9, the IMD was mentioned along with the impact that the use of drugs or alcohol might have upon occupant decisions and ability to escape during a fire. The use of alcohol has been linked with casualties from fires in studies by Holborn *et al.* (2003) and Reynolds (2002).

Another possible further development with the model is the inclusion of discrete decision nodes. This allows a value to be placed to the addition of fire mitigation measures such as sprinkler systems or smoke alarms. FRS performance improvements could also be analysed; for example if the cost to reduce MFRS's response time by 5% was known, it could be factored into the network and weighed up against the savings made from reducing the probability of fatalities and asset damage. This way, cost-benefit analysis could be undertaken. Figure 5.14 provides an example of what the network might look like with the inclusion of two decision nodes (circled), one for improving the performance of FRS travel time and the other for improving call handling at MACC by installing a new call handling system.

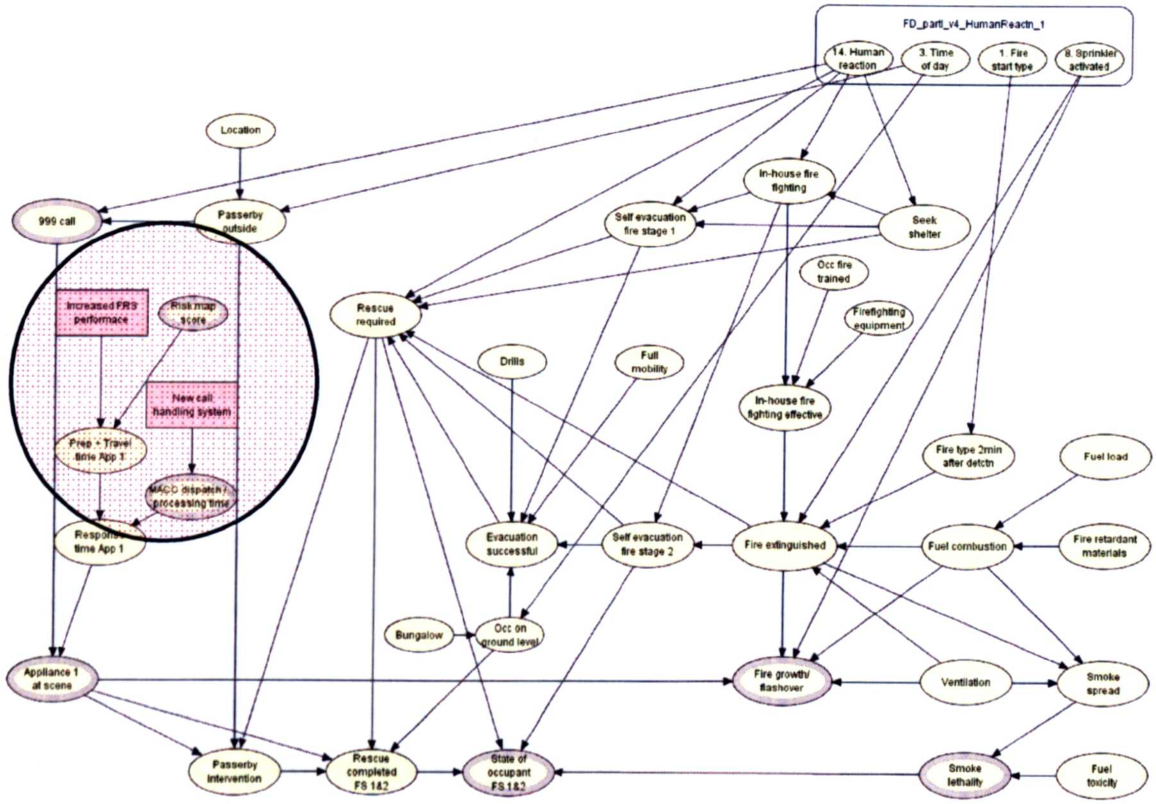


Figure 5.14. Part II of the model with the inclusion of two decision nodes.

5.8 CONCLUSIONS AND BRIEF DISCUSSION

Part II of a BN designed to model dwelling fires has been presented in this chapter. This network links into parts I and III of the overall model. There are thirty four chance nodes representing parameters consisting of FRS response time, occupant actions, fuel characteristics, smoke development, and characteristics about the dwelling including its location. The conditional probabilities have been built based on hard data, information from literature, and expert opinion, using a variety of techniques. Occupant survival and fire growth have been the focus of this part of the model and results have been generated for these parameters. Several case studies have been conducted. Case 1 demonstrates how occupant decisions can have a big impact upon the probability of surviving a fire; it was noted that an occupant's chance of surviving diminishes considerably if they seek shelter within the dwelling fire. Unfortunately this is an action too often associated with children.

Fees (2012) and New Child Safety (2010) point out that it is in the nature of children to hide in the face of fear. It is thus paramount to educate children and the vulnerable on how to act if ever faced with a fire. The actions of occupants were combined with 999 call and FRS response time which are the inputs to overall time of arrival at the fire incident. Although both are important, the FRS response time was more critical to the survival of occupants.

In case 2 the impact of location and LSOA risk level were examined; it was noted that neither have a major impact upon the probability of an occupant remaining trapped in the dwelling. This implies that FRS response is set up in a way that provides relatively equal cover for all. Diminishing probabilities of remaining trapped were noted for increasing levels of risk but it was recognized that this was offset by increasing frequency of incidents associated with higher risk. Case 3 highlights the impact of smoke lethality noting that it was extremely more perilous to attempt to fight a fire in situations where smoke lethality was high. In case 4 effects upon fire growth / flashover are examined; the input nodes were fuel combustion, ventilation, and FRS response. It was observed that when fuel combustion and ventilation conditions are high the probability of fire growth is very high making prompt response from FRS's vital. The final case examines the effect of nodes from part I of the model. This served a dual purpose, firstly to investigate how smoke alarm, sprinklers, and time of day affect an occupant's chances of remaining trapped in a fire, and secondly to demonstrate how part I of the model functions with part II. The BN model thus far has shown to be useful for undertaking dwelling fire analysis from various perspectives. The results can be extrapolated for assessment of residential communities with similar characteristics such as type of housing, level of risk, new homes with sprinkler systems, areas targeted for smoke alarm campaigns, and so forth.

Further developments of part II of the model have been suggested in section 5.7. As with part I of the model, part II can be given a social dimension in which the impact of social deprivation and substance abuse may be studied. It was noted that alcohol is often present in cases of fire casualties. Another possible development of the model could be to include discrete decision nodes. An example of how these would link up with the rest of network was provided in Figure 5.14. Decision nodes could facilitate the undertaking of a cost-benefit analysis to investigate matters such as investing in improving FRS response time, MACC call handling time, or even the installation of sprinkler systems in new homes as suggested in case study 5. Part III of the model incorporates utility nodes which could be used to measure such decisions in terms of their economic value.

CHAPTER 6 – BAYESIAN NETWORK MODELLING FOR FIRE SAFETY ASSESSMENT: PART III - ADVANCED FIRE SITUATION AND CONSEQUENCES

SUMMARY

This chapter continues from where Chapter 5 left off by presenting part III of the BN model covering dwelling fire at an advanced stage. Consequences for the entire model are computed in economic terms through utility nodes. There are nineteen nodes in this part of the network plus an additional nine transfer nodes from parts I and II. Fire spread, FRS intervention, and dwelling characteristics are all modelled with consequences being assessed in terms of harm to the occupant, harm to the firefighter and property damage. Various case studies are presented including examination of how parameters from parts I and II influence the final outcome of the fire. A cost-benefit analysis is undertaken to support the installation of smoke alarms in all homes. Sensitivity analysis reveals parameters which exercise the greatest influence upon the focus node "State of the occupant fire stage 3". The chapter ends by presenting further development work based upon a variable occupancy version of the model.

6.1 INTRODUCTION

In this chapter part III of the BN model addressing the advanced fire situation in a dwelling is presented. This completes the core part of the model in which dwelling fires can be analysed from start to finish. Figure 6.1 presents a view of the three core parts of the model with part III highlighted; both parts I and II link up with part III. There are various outputs to the integrated model displayed in terms of casualties and property damage within part III; these consequences have also been expressed in monetary units.

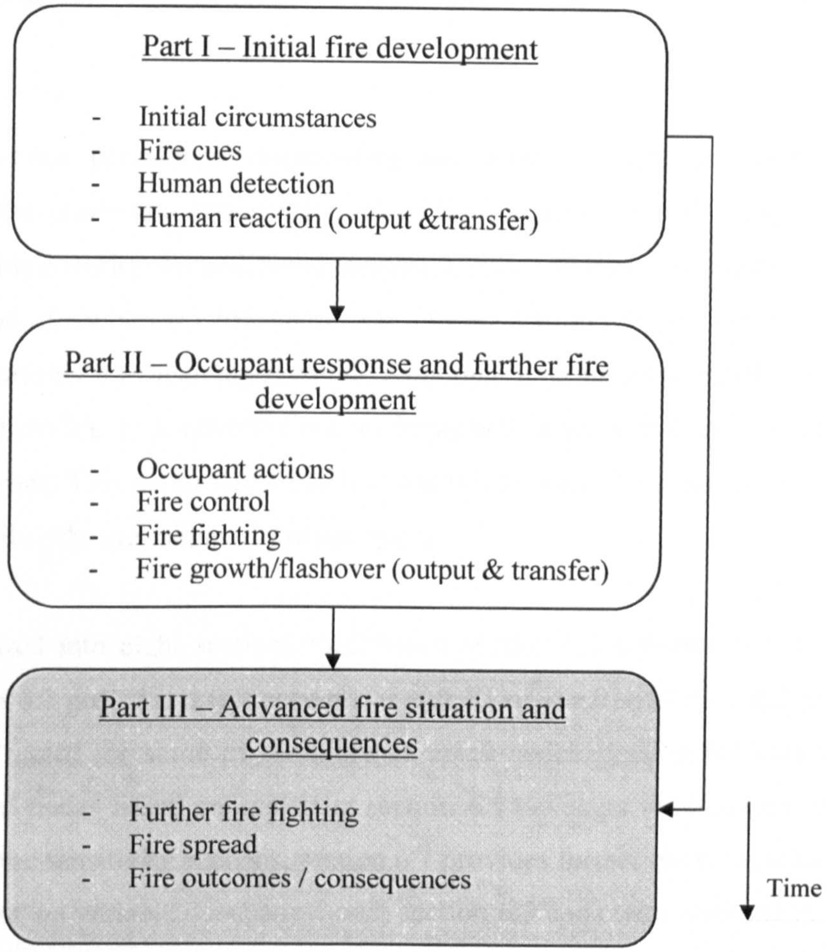


Figure 6.1. Flow chart of events within each part of the BN model

Part III of the model deals in particular with the spread of fire throughout the dwelling. The growth and spread of fire depends on many factors as described in Chapter 5. Once the flames of a fire reach the ceiling it begins to expand very rapidly as high temperatures disperse around the dwelling. Heat is transferred quickly and many items reach their combustion point. This is far more likely to happen when doors are open and flashover has occurred. Most doors will not contain a fire for long and can even quickly become part of the fuel load. Fire doors however will contain a fire for a specified length of time as described below in section 6.2.4. Aspects of fire growth and spread are discussed further in

Yung (2008), Hadjisophocleous *et al.* (2007), Stollard and Abrahams (1999), and Platt *et al.* (1994).

The model incorporates parameters representing the spread of fire and containment measures such as fire doors and intervention of FRS's. Arrival time of FRS's is again represented but on this occasion for additional support. Links with part II of the model allow for the time of arrival of appliance 1 to be assessed. Fire escalation into other dwellings and firefighting complications are also represented. Although it is extremely unlikely for a firefighter to lose their life it is nevertheless an important issue and therefore has been included in the network. This parameter feeds into the utility node "Human cost £" as well as the node representing the wellbeing of the occupant.

Chapter 6 is structured into eight sections as follows: section 6.1 consists of the current introduction; section 6.2 provides a full account of part III of the BN; section 6.3 explains how data was constructed for some of the more complex nodes; section 6.4 outlines the calibration of several nodes based on statistics; section 6.5 develops various case studies; section 6.6 presents the sensitivity analysis; section 6.7 provides further developments of the whole model focusing on variable occupancy, and; section 6.8 ends with conclusions and a brief discussion.

6.2 PART III OF THE MODEL - ADVANCED FIRE SITUATION AND CONSEQUENCES

Part III of the model was built following the same eleven step procedure used for the other model parts, described in Chapter 4 section 4.3.1.1. Once linked with parts I and II a complete analysis of a dwelling fire from start to end could be undertaken. Thought then had to be given on the best way to measure results. It was decided that two utility nodes should be included. These are briefly discussed below along with some other observations about the model, before the actual network content and structure are introduced.

6.2.1 Utility nodes

Part III of the model represents the final stages of the fire and quantifies losses economically through two utility nodes. The utility nodes model the losses based on the probability of various outcomes. Essentially this provides a measure of risk to which experts can relate. The results can then be used to analyse how different risk reduction ideas would compare against the levels of investment required. In this way cost-benefit studies could be conducted with the model.

Utility nodes link up within the network in a similar way to chance nodes; however they cannot have child nodes and hence are at the end of the network. They are represented by a green diamond box.

6.2.2 Continuous data represented through discrete nodes

The need to represent continuous parameters through discrete nodes has been addressed in Chapter 5, section 5.2.2. Part III of the model includes the following three time based nodes:

- Preparation + travel time additional support
- Response time additional support
- Additional support at scene

6.2.3 Assumptions and limitations

6.2.3.1 Space / time limitations

As explained in chapter 5 section 5.2.3.1 the model incorporates various time-based probabilities. Within part III the nodes in question are at *fire stage 3* which is the advance phase of the fire when fire size could range from small to large depending on various factors such as how effective fire fighting measures had been. A large fire implies it has spread from the room of origin into other compartments or even an adjoining dwelling. Fire stage 3 is the final phase of the fire and thus there is no upper time boundary.

6.2.4 Nodes and structure

The third part of the BN (Figure 6.2) is built to model the advanced stages of a dwelling fire and consequences. Note that those fires which are extinguished in part II of the model would render this part of the model meaningless except for the utility nodes used to quantify potential losses. There are several aspects of the advanced fire situation which can be examined with part III of the model, namely:

- The impact of FRS response time and intervention of both the first appliance and additional support.
- The influence of the setting in terms of the dwelling characteristics.
- The development of fire based on interaction with various parameters.
- The effect of fire development upon the wellbeing of the occupant and firefighters.
- The effect of fire development upon the dwelling structure.
- The impact on life and assets in terms of economic value.

The focus of this part of the model is human wellbeing and property damage through the nodes “State of the occupant fire stage 3”, “Human cost £”, and “Property damage £”.

There are eight transfer nodes linking part II to part III of the model; these are “999 call”, “Risk map score”, “MACC dispatch / call processing time”, “Appliance 1 at scene”, “Fire growth / flashover”. “State of the occupant fire stage 1&2”, “Smoke lethality”, and “Fire extinguished”. Only one transfer node, “Sprinkler activated”, links directly from part I to part III. Part I is linked entirely to part III through part II of the network.

The reasoning behind each of the nineteen nodes of part III of the network is explained below. As with part II of the model, part III is complex and requires a more comprehensive account than part I. The nodes are grouped into *pre-conditions, FRS interaction, occurrences / fire development,* and *utility nodes*; they are arranged firstly according to category and secondly according to chronological interaction within the network.

Pre-conditions:

1. Fire doors present and shut [state: Yes, No] – This parentless chance node embodies two factors, the first is the presence of self-closing fire doors within a dwelling, the second is the condition that they are shut during the fire. When completely shut fire doors are effective at containing fires within a compartment / room for a specified period of time, typically 20 to 30 minutes; this time will be dependent upon the construction of the door, specifically the materials used and the door thickness. Fire doors are sometimes classed as either *smoke stop doors* or *fire resisting doors* but for the purpose of this study are considered as one group with the capacity to provide resistance to fire, smoke, and heat spread. Data on the existence of fire doors within dwellings, that is the first factor contained within this node, is scarce. Literature indicates that self-closing fire doors are primarily a feature of newly built homes (McDermott *et al.*, 2010). If all dwellings are taken into account the proportion of those with self-closing fire doors is minimal. Manual closing fire doors do however feature in a greater percentage of homes; this will boost the overall housing stock probability of having such doors. Regarding data for the second factor, that is the fire door being shut, it has been documented that self-closing fire doors in dwellings are nearly always tampered with resulting in them not closing properly or at all (McDermott *et al.*, 2010); this also occurs but to a lesser extent in office buildings (Harvard University, 2012). Manual fire doors in dwellings are also generally left open.
2. Adjacent dwelling [states: Yes, No] – This parentless chance node describes the presence of another dwelling which is either adjoined / contiguous to the dwelling on fire, or which is separated by a distance of less than 2 metres; an example of the former would be a terraced property and the latter a series of small detached properties as demonstrated in Figure 6.2. Data for this node was compiled from the English Housing Survey (Communities and Local Government, 2010c).

Figure 6.2. An example of closely packed detached dwellings on the Wirral.

FRS interaction:

3. Preparation + travel time additional support [states: <5m, 5 to 10m, >10m] – This chance node is similar to "Preparation + travel time appliance 1" (from part I of the model), except for the fact it is modelling the dispatch of *additional support*, that is appliances 2 and 3; if a third appliance is sent to the scene it typically arrives very close to the time of the second appliance, therefore for the purpose of this model appliances 2 and 3 can be considered together under the banner of *additional support* in similar fashion to MFRS's response standards. For a description of this node see "Preparation + travel time appliance 1" contained in Chapter 5, section 5.2.4. The node's conditional probabilities are set in line with its sole parent node "Risk map score" which is a transfer node from part II. Details of how the CPT was constructed is presented in section 6.3.
4. Response time additional support [states: <5m, 5 to 10m, >10m] – This chance node is similar to "Response time appliance 1" except it is modelling the response time of *additional support*. For a description of this node see the aforementioned part II node in Chapter 5, section 5.2.4. The node's conditional probabilities are set according to its parent nodes "Preparation + travel time additional support" and

"MACC dispatch / call processing", the latter of which is a transfer node from part II. Note that the CPT is the same as its namesake from part II since it is also combining two time nodes with the same states.

5. Additional support at scene [states: <5m, 5 to 10m, >10m] – As with the previous two nodes, this chance node is the same as its namesake from part II of the model except it is dealing with *additional support* rather than *appliance 1*; see Chapter 5, section 5.2.4 for a description. The node's conditional probabilities are set according to its parent nodes ""Response time additional support" and "999 call" which is a transfer node from part II. Once again the CPT is the same as its namesake from part II since it is also combining two time nodes with the same states.

Occurrences / fire development:

6. Bridge node Fire extinguished [states: Yes, No] – This node is a replica of the part II transfer node "Fire extinguished" and has been included to avoid overlay of *arcs* upon certain nodes and thus facilitate the understanding of the network diagram. Its sole parent node is the transfer node "Fire extinguished".
7. Fire spread to other compartments [states: Yes, No] – This chance node describes the spread of fire from the room of origin to any other room within the dwelling including those on floors above or below. Fire can spread either through an open door, by burning through a door, wall, or ceiling, by burning along a floor beneath a door, or even by flames bursting through a window on one floor into one on another floor. The prime requirement for fire spread from one room to another is that fire grows or reaches a state of flashover. Note that the physics behind fire growth / flashover are not represented here as this requires numerical modelling of the dynamics of fire which must take into account factors such as the geometry of the compartment, ventilation conditions, fuel characteristics, and heat propagation. The mechanisms which control some of these factors and hence the probability of fire spread are however considered, namely fire doors, FRS intervention, and sprinkler activated. The node's conditional probabilities are set in accordance with its six parent nodes "Fire extinguished", "Fire growth / flashover", "Appliance 1 at scene",

"Additional support at scene", "Fire doors present and shut" and "Sprinkler activated"; the first three of these are transfer nodes from part II of the BN while the last a transfer node from part I. The logic behind the CPT is as follows: If there is no flashover and fire doors are present and shut then the chance of fire spread is very low as indicated in the CPT (Appendix 10). The arrival of the first appliance would be able to deal with the situation when there is no fire growth / flashover so that the timing of arrival of additional support would have negligible bearing upon the probability of fire spread to other compartments. When there is no flashover each 5 minute delay of the first FRS appliance doubles the chance of fire spread. The impact of shut fire doors is to halve the probability of fire spread; in this study it is assumed that they would contain a fire for 20 minutes when shut. When there is fire growth / flashover the probabilities of fire spread in the CPT increase considerably. Again each 5 minute delay of the first FRS appliance doubles the probability of fire spread. Each 5 minute delay of additional support adds 0.025 to that probability. For cases where the fire doors are open each 5 minute delay of the first appliance adds 0.15 to the already elevated probability of fire spread, while each 5 minute delay of additional support adds 0.05. If a sprinkler system is activated the probability of fire spread is halved. The node "Fire spread to other compartments" described here, subsequently feeds into the utility node "Property damage" which attempts to quantify economically the damage incurred by the fire.

8. Structural failure / collapse [states: Yes, No] – This chance node describes the potential for structural failure and collapse of part or all of the dwelling. This includes sections of roofs caving in, ceiling buckling, walls collapsing, or even an entire dwelling crumbling to the ground. This may occur because of buckling of steel girders with heat leading to a loss of their load bearing capacity. Other materials might burn to ashes and fail to support loads. The conditional probabilities of this node are set in line with its sole parent node "Fire spread to other compartments". The structural integrity of a dwelling during a fire will depend upon the size / spread of the fire, but also upon the materials it is constructed out of and how it has been engineered. The latter information is difficult to obtain yet alone

quantify and therefore is not represented through a node but rather assumed within the conditional probability of the node being described. This node is also important because it subsequently feeds into the utility node "Property damage".

9. Fire spread to other dwellings [states, Yes, No] – This chance node represents a situation in which a fire has grown beyond the original dwelling and spread into a neighbouring dwelling. For the node to be true it is sufficient for the contiguous structure to be on fire anywhere including exterior parts such as a roof. The node's conditional probabilities are set in accordance with its parent nodes "Appliance 1 at scene", "Bridge node Fire extinguished", "Additional support at scene", "Fire spread to other compartments", and "Structural failure / collapse"; the first of these is a transfer node from part II of the BN. "Fire spread to other dwellings" is also important because it feeds into the utility node "Property damage".
10. Second rescue attempt required [states: Yes, No] – This chance node represents a person remaining trapped following an unsuccessful first rescue attempt during fire stages 1 and 2, hence a second rescue attempt is required. The purpose of this node is to reduce the size of the CPT of the node "Rescue successful FS3" by acting as an intermediate node between "State of the occupant FS 1&2" and "Rescue successful FS 3"; this is achieved by dropping the states "alive – well/minor injury", "alive – major injury", and "dead". The node's conditional probability is set according to its sole parent node "State of the occupant fire stage 1&2".
11. Firefighting complications [states: Yes, No] – This chance node describes the situation of firefighting becoming highly complicated and challenging; this does not imply that dwelling firefighting is straightforward but rather accentuates situations in which fires grow to the extent that the structure of the dwelling is affected or the dwelling boundaries are exceeded; essentially the node seeks to represent circumstances in which a contained dwelling fire turns into a precarious potential multiple-dwelling fire. The purpose of the node is to model scenarios which adversely affect rescue attempts and endanger firefighters lives by entrapment. The node's conditional probabilities are set in relation to its parent nodes "Structural failure / collapse" and "Fire spread to other dwellings".

12. Rescue successful fire stage 3 [states: Yes, No] – This chance node represents the event of the occupant being rescued successfully while the fire is still ongoing. The term "successful" refers to the complete physical extraction of the occupant while alive hence an unsuccessful rescue means that the occupant has lost his/her life. Once extracted their actual state of health is captured in a subsequent node "State of occupant fire stage 3". The key difference between the node being described and a similar node "Rescue completed fire stage 1&2" from part II of the model is that if the latter is not true the occupant can be either dead or trapped / in an unknown condition. The conditional probabilities of the node "Rescue successful fire stage 3" are set in line with its parent nodes "Second rescue attempt required", "Fire spread to other compartments", "Additional support at scene", and "Fire fighting complications".
13. State of the occupant fire stage 3 [states: Alive – well/minor injury, Alive – major injury, Dead] – This chance node describes the living status of the dwelling occupant at the more advanced fire stage. The three states for this node have already been described under the node "State of the occupant fire stage 1 & 2" found in part II of the model (Chapter 5 section 5.2.4). The key difference between the two nodes is that the latter has an additional state "Trapped"; however in part III of the model an outcome must be reached on the living status of the occupant which is why the state "Trapped" is dropped. The conditional probabilities of the node being described are set in accordance with the state of its parent nodes "State of the occupant fire stage 1&2", "Smoke lethality", "Fire spread to other compartments", and "Rescue successful fire stage 3"; note that the first two of these parents are transfer nodes from part II of the BN. The node being described here integrates the probability of survival from parts II and III of the model. It is of particular importance because it serves as a means of measuring the degree of human safety of a particular fire situation, subsequently feeding into a utility node "Human cost £" which attempts to quantify financially the value of human life.
14. Number of firefighters in dwelling [states: 0, 1, 2, 3, 4] – This chance node represents the number of firefighters physically present inside the dwelling.

Firefighters typically move within buildings in teams that are coordinated externally by a fire officer. The fire fighting tactics employed vary from incident to incident and modelling precisely the number operating within a building at any one time would require a more dynamic model. In this BN the number of firefighters within a dwelling is captured coarsely in accordance with three factors: firstly by the condition of whether the fire has been previously extinguished represented through the node "Bridge node Fire extinguished"; secondly by the size of the fire captured through the node "Fire spread to other compartments", and; thirdly by the urgency of firefighting reflected through the node "Second rescue attempt required". The conditional probabilities of "Number of firefighters in dwelling" are thus set in accordance with these three nodes. The number of firefighters within the dwelling needs to be known only at the time when fire fighting complications develop, thus, nodes from part II do not need to be included in forming the conditional probabilities of this node.

15. Firefighter rescue required [states: Yes, No] – This chance node indicates that one or more firefighters have become trapped and that their safety is compromised thus rescue is required. Situations like these are rare but can arise when fires become large and complicated leading to possible structural collapse of part of a dwelling for example the roof or walls, or even fire spreading to adjacent properties. The conditional probabilities of this node are set according to the state of its parent nodes "Number of firefighters in dwelling" and "Firefighting complications".
16. Firefighter rescue successful fire stage 3 [states: Yes, No] – This chance node represents the event of the firefighter being rescued successfully while the fire is still ongoing. The term "successful" refers to the complete physical extraction of the firefighter while alive hence an unsuccessful rescue means that the firefighter has lost his/her life. Once extracted, their actual state of health is captured in a subsequent node "State of firefighter". The conditional probabilities of the node "Firefighter rescue successful fire stage 3" are set in line with its parent nodes "Firefighter rescue required" and "Additional support at scene".

17. State of firefighter [states: Alive – well/minor injury, Alive – major injury, Dead] – This chance node describes the living status of the trapped firefighter following an attempted rescue. There are three states for this node. The first state "alive – well / minor injury" entails either no injury or a relatively small injury such as broken bones, cuts, bruises, trauma, shock, and other conditions from which a person would normally fully recover from. The second state "alive – major injury" involves damage such as a broken back, long term scarring / burns, life threatening injuries, and other conditions from which a person may never fully recover. The third state "Dead" signifies that the firefighter has lost his/her life. Note that, as with the node "State of the occupant FS 1&2", sometimes people with major injuries for example fractured skull, internal bleeding, heart failure, poisoning from smoke, *etc.*, lose their life shortly after being rescued or escaping from an unsafe situation, therefore this node considers the condition of a firefighter up to 15 minutes after rescue or escape has occurred. After this period other factors become more influential such as intervention from ambulance and medical teams. This node's conditional probabilities are set in accordance with the state of its parent nodes "Firefighter rescue fire stage 3" and "smoke lethality", the latter of which is a transfer node from part II. Note that the effect of smoke upon firefighters is much less compared to the occupant since the former typically enter a burning property with breathing apparatus. The wellbeing of firefighters is of prime importance at all times; this node is therefore valuable as it measures the safety of firefighters in situations of complicated and advanced dwelling fires. The node also feeds into the utility node "Human cost £".

Utility nodes:

18. Property damage £ [utility] – This utility node quantifies the consequence of property damage in £. Data has been compiled based on information provided by the Land Registry (2012). For cases when there is structural collapse, demolition costs have been factored into the figures. The utilities have been compiled based on the parent nodes "Fire growth / flashover" (part II), "Fire spread to other compartments", "Structural collapse", and "Fire spread to other dwellings".
19. Human cost £ [utility] – This utility node quantifies economically the consequences of casualties in terms of loss of life, alive with major injury and alive well or with minor injuries. The values used are £1.5 million and £155,000 for the first two possibilities derived as explained in Chapter 2, section 2.2.4.3; £100 has been used as a mean figure for being well or having minor injuries. The utilities have been compiled based on the parent nodes "State of firefighter" and "State of the occupant fire stage 3".

As with part II of the network there are also two versions of part III, the first is the 'risk-map' linked version, the second the 'Fire time response module' (or part IV) linked version. The 'risk-map' linked version functions independently from part IV of the model with FRS response time based upon the level of risk assigned through MFRS's risk map. The 'risk-map' linked version which is the one being presented in this chapter is given in Figure 6.3; the 'Fire time response module' linked version is provided in Chapter 7, section 7.6. Nodes have been structured so that events flow from top to bottom where possible; utility nodes (the green diamond boxes) are located towards the right of the network. Similar themed nodes have been kept in proximity to each other. The transfer nodes are located at the top of the network with those from part II towards the left and part I towards the right.

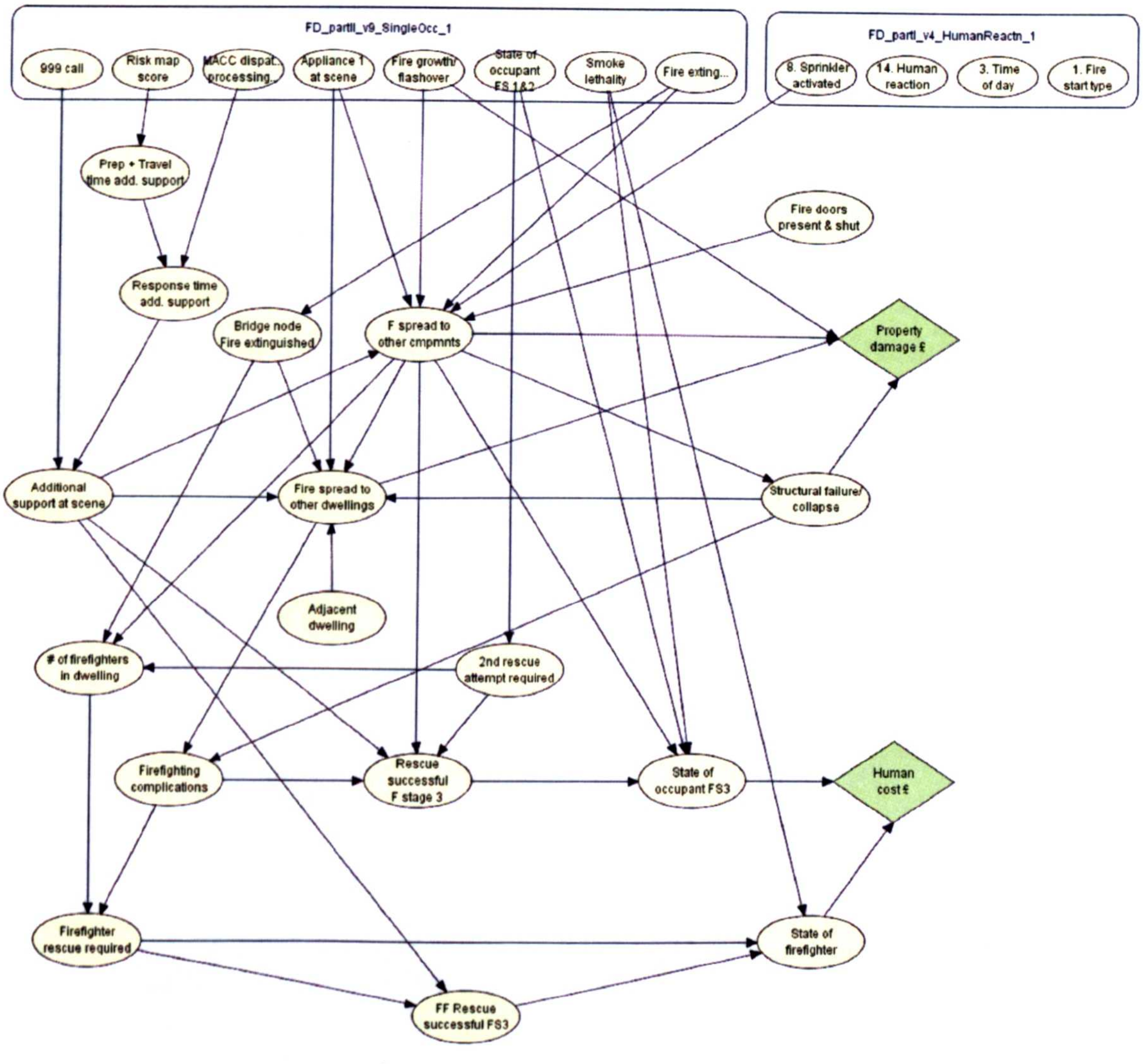


Figure 6.3. BN Model Part III ('risk-map' linked version) representing advanced fire situation and consequences.

6.2.5 Note on parameters excluded from the network

The above nodes are considered the most important in modelling the development of fire at an advanced stage. There is however one other factor that plays a part in defining the development of a fire and its consequences and that is the effectiveness of firefighting. The reason this is not included is because specific action at an incident would be too complex to represent at this stage. It would require considering the particulars of appliances, the training and experience of firefighters, levels of stress, communication, water pressure, access to property, and so forth. In light of this, the model assumes that firefighting action is equally effective on all occasions.

6.2.6 Model d-separation

A d-separation test has been conducted as defined in Chapter 4, section 4.2.4 to demonstrate that the model has been simplified and that there are no superfluous nodes. Figure 6.4 provides the result for the focus node set on "State of the occupant fire stage 3", the nodes which are *d-separated* (relevant) have a tick, and those which are *d-connected* (irrelevant) have a cross, in this case none. The transfer nodes from part I of the network and the utility nodes have been deleted to allow d-separation to be performed with Hugin. D-separation checks have also been conducted for other part III nodes the ensure network relevance of respective influencing nodes.

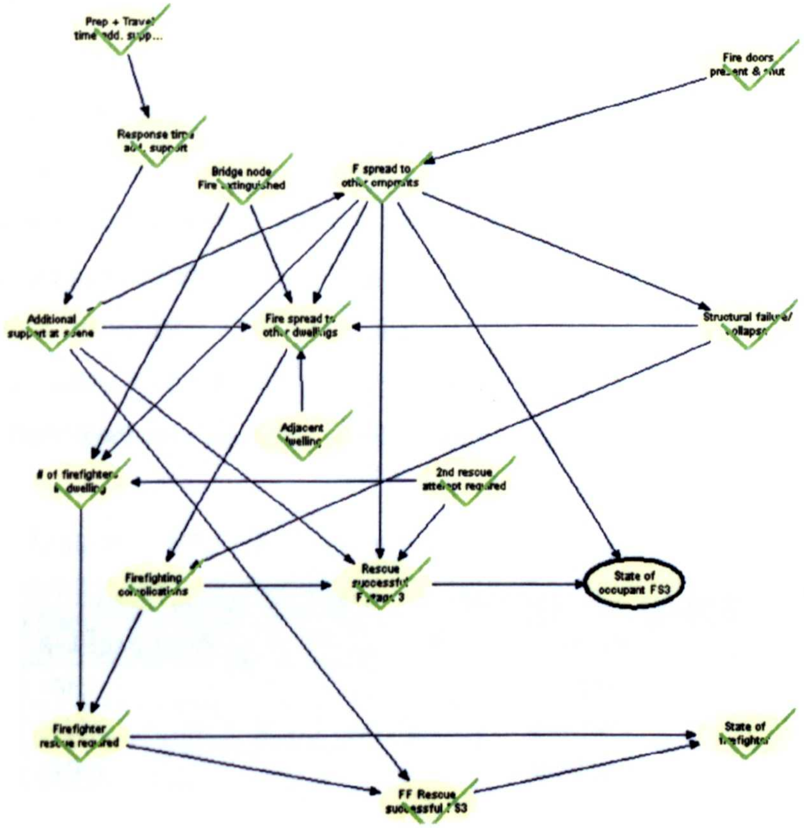


Figure 6.4. BN Model Part III showing d-separation for the focus node "State of the occupant FS 3".

6.3 DATA FOR THE BN MODEL – PART III

6.3.1 Node connections and construction of CPTs

The third part of the model features nineteen nodes connected via serial, diverging, and converging *arcs*. There are two nodes with sextuple converging connections and two with quadruple converging connections. Constructing some of the CPTs was once again a unique challenge since directly applicable data did not exist. Expert opinion and various discerning sources of information had to be used. The following paragraphs outline how some of the CPTs were constructed; note that all part III CPTs are provided in Appendix 10:

- Node: Preparation + travel time appliance 1 [states: <5 minutes, 5 to 10 minutes, >10 minutes]. The data for this node was built based on the assumption that the result should reflect the conditions of the response standards for the arrival of additional support. Thus if the dwelling was in a high risk area additional support should arrive within 10 minutes, medium risk area within 11 minutes, and low risk area within 12 minutes; furthermore this should be true on 90% of occasions in line with actual MFRS performance. Assuming an equal distribution of response 0.9 / 2 was inserted in the top left cell under the condition [High] risk for the state [<5m] of "Preparation + travel time additional support" (Table 6.1). The subsequent cell therefore must also have been 0.45 to be within 10 minutes. The remainder 0.1 was placed into the slot for [>10m]. A similar procedure was followed for the other risk conditions (*i.e.* medium and low) based on their respective response times as defined by MFRS.

Table 6.1. CPT for "Preparation + travel time additional support.

Prior CPD for "Preparation + travel time Add. Support"			
Risk map score	High	Medium	Low
<5m	0.45	0.40909	0.375
5-10m	0.45	0.40909	0.375
>10m	0.1	0.18182	0.25

- Fire spread to other compartments [states: Yes, No]. This node has 288 permutations. The following assumptions were made in the construction the CPT:

  - If fire was extinguished there could not be fire spread.
  - For FRS response: During conditions of fire growth / flashover, if no sprinkler is activated and a fire door is present and shut, each 5 minute delay of appliance 1 increases the probability of fire spread to another compartment by 20%, while each 5 minute delay of additional support by 3%. If fire doors are not shut the probabilities increase by 50% with the delay of appliance 1 and 20% with delay of additional support. If fire growth / flashover does not occur the probabilities of fire spread are virtually none existent. Still, the effect of delay in appliance 1 doubles the probability of fire spread.
  - If sprinklers are activated all probabilities are divided by 10 based upon expert opinion stating that sprinklers are effective on *circa* 90% of occasions.
  - The arrival of additional support cannot occur before appliance 1 which is reflected in the probabilities.

- Fire spread to other dwellings [states: Yes, No]. This node also has 288 permutations. The assumptions made in building the CPT are provided below and have been based on reviewing literature and discussions with experts:
  - If fire was extinguished it cannot spread to another building
  - By this stage the fire is so large that most of the dwelling is gutted rendering any sprinkler ineffective.
  - Fire spread to an adjacent dwelling can only occur if there is a neighbouring attached property (terraced or semi-detached) or if the detached dwelling is within 2 metres.
  - The node cannot be true if fire has not spread beyond the room of origin unless there has been structural collapse.
  - For FRS response: Each 5 minute delay of appliance 1 doubles the probability of fire spread to another dwelling if fire has already spread beyond the room of origin and structural collapse has occurred. Each 5 minute delay of the additional appliance adds 5% to the probability. If structural collapse has not occurred the probability is halved.

6.3.2 Summary of node data content

Table 6.2 summarizes the node content for part III of the model. Details are provided on the number of states, parent nodes, number of permutations in the CPT, and the types of sources of information. Specific sources of literature are not named in the table but are included within the text where relevant. For example the CPT for node 1 has been completed based on information from the English Housing Survey (Communities and Local Government, 2010c), McDermott *et al.,* and Harvard (2010). In Table 6.2 the nodes have been grouped by theme with the utility nodes placed at the end as outputs to the network. The compilation of data for each node has been discussed in sections 6.2.4 and 6.3.1.

Table 6.2. Probability table details for each node and origins of data for part III.

Node #	Node name	# of states	# of parent nodes	# of permu-tations in prob. table	Probabilities compiled from	Subjec-tive element
Transfer nodes from part I of the mode.						
8	Sprinkler activated	2	2	4	Literature	Yes
Transfer nodes from part II of the mode.						
14	999 call	3	2	12	Exp. op., literature	Yes
12	Risk map score	3	0	3	MFRS	No
20	MACC dispatch / call prcess. T	3	0	3	Questnnr., exp. op.	Yes
23	Appliance 1 at scene	3	2	27	MFRS, see App 7	No
30	Fire growth / flashover	2	5	96	Exp. op., literature	Yes
34	State of the occupant FS 1&2	4	4	64	Exp. op., literature	Yes
32	Smoke lethality	2	2	8	Exp. op., literature	Yes
Part III: Pre-conditions						
1	Fire doors present and shut	2	0	2	Literature	Yes
2	Adjacent dwelling	2	0	2	Exp. op., literature	Yes
Part III: FRS interaction						
3	Prep. + travel time add suppt.	3	1	9	MFRS resp. stand.	No
4	Response time add. support	3	2	27	MFRS, see App 7	No
5	Additional suppt. at scene	3	2	27	MFRS, see App 7	No
Part III: Occurrences / fire development						
6	Bridge node Fire extinguished	2	1	4	Transfer node	n/a
7	Fire spread to other comprtmts.	2	6	288	Exp. op., literature	Yes
8	Structural failure / collapse	2	1	4	Exp. op., literature	Yes

9	Fire spread to other dwellings	2	6	288	Exp. op., literature	Yes
10	Second rescue attempt required	2	1	8	Event logic	No
11	Firefighting complications	2	2	8	Expert opinion	Yes
12	Rescue successful FS 3	2	4	48	Exp. op., literature	Yes
13	State of the occupant FS 3	3	4	96	Exp. op., literature	Yes
14	Number of firefighter in dwelling	5	3	40	Expert opinion	Yes
15	Firefighter rescue required	2	2	20	Exp. op., literature	Yes
16	Firefighter rescue successful FS3	2	2	12	Exp. op., literature	Yes
17	State of the firefighter	3	3	24	Exp. op., literature	Yes
Part III: Utility nodes						
18	Property damage £	1	4	16	Literature	No
19	Human cost £	1	2	9	Literature	No

6.4 PRIOR PROBABILITY CALIBRATION

Prior probabilities / values of focus nodes and those with complex CPTs were compared against statistics in order to calibrate the model; the nodes which were selected were chosen for the same reasons outlined in Chapter 5, section 5.4, in which part II of the model was calibrated. If the difference between the figures was minor then respective small adjustments were made to the probabilities; if the differences were large then the relevant section of the network was reviewed. Once calibrated a final comparison with statistics was carried out revealing that the nodes were representative of reality. The following were the nodes checked; note that probabilities are expressed out of 100 as given in the Hugin software:

- Fire spread to other compartments: Prior probabilities were [Yes: 9.58, No: 90.42]. These figures were compared with UK fire spread statistics from Stollard and Abrahams (1999) which show that fire spread beyond the room of origin on 9% of occasions. These values were very close to the each other and more than acceptable for the model. Note that although the statistics are around 15 years old they are still valid today since fire behaviour in dwellings changes very slowly over time.

- Fire spread to other dwellings: Prior probabilities were [Yes: 1.04, No: 98.96]. These probabilities were compared again with UK fire spread statistics from Stollard and Abrahams (1999) which indicate that fire spread beyond the original dwelling on 1% of occasions. The model values again compare well with statistics with a difference of only 0.04 (normally expressed 0.0004 as a probability).

- State of the occupant fire stage 3: Prior probabilities were [Alive – well / minor injury: 87.10, Alive – major injury: 12.18, Dead: 0.72]. Using annual statistics from Communities and Local Government it was possible to estimate the probability of fatality in each dwelling fire. The way the figure was derived has been explained in Chapter 5, section 5.4. The value calculated was 0.7% which is close to figure from the model. The higher value produced by the model has been attributed to the fact that it is tailored for Merseyside where the rate of fatalities is higher than average.

- State of the firefighter: Prior probabilities were [Alive – well / minor injury: 99.98, Alive – major injury: 0.02, Dead: 0.00333]. The probability of fatality of a firefighter was estimated based on information provided by The Fire Brigades Union (2008). The report states that between 1978 and 2006 forty four firefighters lost their lives in building fires in the UK which equates to a rate of 1.6 per year. More recent figures for England indicate that 8 firefighter deaths were recorded in building fires between 2000 and 2006 which also equates to 1.6 per year. The number of building fires was then computed from statistics provided by Communities and Local Government (2011b). There were 91,800 primary fires in 2010 of which 59% were building fires, equating to 54,162. To obtain the probability of fatality of a firefighter in a dwelling fire the rate of death per year was divided by the number of fires:
  1.6 / 54,162 = 0.00003, expressed as a probability out of 100 as 0.003. This value was very close to that of the model with a difference of only 0.00033 making this output also valid.

- Utility node Human cost £: Prior utility [29,975]. This economic measure of the consequences of fire in terms of human life was compared to data derived from the latest set of figures on the economic cost of fire corresponding to the year 2008 for England (Communities and Local Government, 2011c), in combination with the number of dwelling fires in England between 2008 and 2010 (Communities and Local Government, 2011b). The figure for comparison was obtained as follows:

  Total cost of fatal and non-fatal casualties = £1.402 x 10^9
  Percentage of fatalities corresponding to dwelling fires = 79%
  Cost of casualties from dwelling fires = 1.402 x 10^9 x 0.79 = £1.106 x 10^9
  Average number of primary fires 2008 to 2010 = 99,000
  Percentage of dwelling fires = 38%
  Number of dwelling fires = 99,000 x 0.38 = 37,017
  Cost of Human casualties per fire = 1.106 x 10^9 / 37,017 = £29,921

  Data on the cost of fire in terms of human life was only available as a combined figure for fatalities and injuries. The value provided by the model was just £54 higher than the value derived from statistics which is very acceptable.

- Utility node Property damage £: Prior utility [28,206]. The economic measure of fire in terms of property damage was compared with a figure derived from data from the same two sources from Communities and Local Government (2011b and 2011c) as above. The figure was computed as follows:

  Total cost of property damage from primary fires = £1.490 x 10^9
  Number of building fires = 54,162
  Cost of building damage per fire = 1.490 x 10^9 / 54,162 = £27,584

The model value compares well with statistics. The difference can be attributed to the latter being inclusive of all building types including premises such as outdoor storage, garages, *etc.*, whilst the model is built for dwellings only.

Table 6.3 provides a summary of the nodes which were compared with statistics. Columns 4 and 5 contain the statistic source and value; column 6 provides the difference between the model prior probability or economic value and the relevant statistic.

Table 6.3. Summary of nodes that were checked for consistency of prior probabilities and economic values with 'real world' statistics (note probabilities are expressed out of 100).

Node	Prior probability state	Prior probability for state / value	Statistic region and period:	Statistic	Model to stats difference
Fire spread to other compartnts.	Yes	9.58	UK, 1992*	9.00	0.58
Fire spread to other dwellings	Yes	1.04	UK, 1992*	1.00	0.04
State of occupant FS3	Dead	0.72	UK, 1996-2010*	0.70	0.02
State of the firefighter	Dead	0.00333	UK 1978-2006*	0.003	0.0003
Human cost £	Utility	£29,975	England, 2010*	£29,921	£54
Property damage £	Utility	£28,206	England, 2010*	£27,584	£1,144

* References for this data are provided in the text within section 6.4.

6.5 MODEL PART III CASE STUDIES

Part III of the model was applied to investigate how the behaviour of various parameters combines to influence the consequences of a dwelling fire when at an advanced stage. Posterior probabilities are computed for nodes of interest given specific evidence through the *run mode* of Hugin. The focus of part III of the model is on fire spread, human rescue, and consequences in terms of human life and dwelling damage. These factors are influenced by performance of FRS's and dwelling characteristics, but also by all nodes from part I and II. FRS performance covers response time and number of firefighters; dwelling characteristics includes compartmentation and proximity to other dwellings.

With the model now fully integrated parts I, II and III can be used to study the entire fire process in a dwelling, as well as the consequences in economic terms. Case studies are presented below focusing both on the model as a whole and on the sole interaction of part III nodes. The rationale for developing each case study are also explained.

Case 1 – Fires spread, FRS preparation plus travel time (appliance 1 v additional support), effect upon fatality

The spread of fire in any type of building will hamper escape and rescue which hence will result in a higher probability of fatality. In this case study the effect of fire spread from the room of origin is examined. This is combined with different response times of FRS appliances to provide a probability of fatality. In both tests the time for "999 call" and "MACC dispatch / call processing time" are each fixed at <1m; this is done in order to isolate the effect of FRS crew preparation plus travel time, upon the probability of fatality. *Test 1.1* presents the case for the first appliance whilst *test 1.2* for additional support and these are compared to determine how critical a delay of each would be.

Test 1.1: Figure 6.5 presents the probabilities of fatality based upon fire spread and the preparation plus travel time element of response time of the first appliance. Clearly it can be seen that once a fire spreads beyond the room of origin the chance of survival drops considerably. In such situations it is likely that smoke would have spread throughout most of the dwelling and the fire would be blocking escape routes. The prompt arrival of appliance 1 is far more critical in such circumstances. If appliance 1 was to arrive after 10 minutes from the moment of notification the chance of survival would be almost three times less compared to arriving within 5 minutes; if the fire had not spread survival chance would be just over one and a half times less when comparing first appliance response time of [>10m] with [<5m].

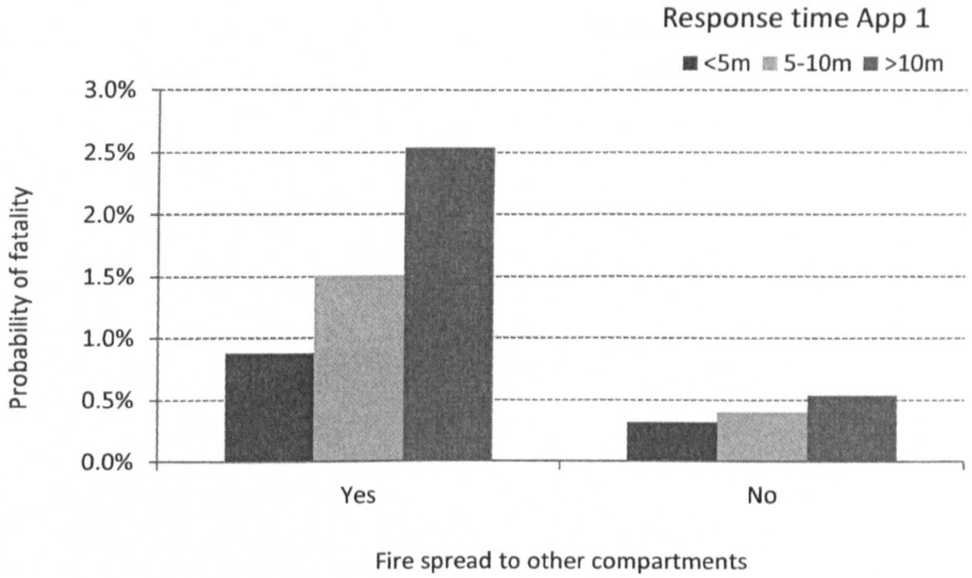


Figure 6.5. Effect of fire spread into other compartments and response time Appliance 1 on posterior probabilities of the node "State of the occupant fire stage 3" [state: Dead].

Test 1.2: Figure 6.6 presents the probabilities of fatality based upon fire spread and the preparation plus travel time element of response time of the additional support. Note that the response time of appliance 1 has been fixed at <5m in order to solely test the effect of additional support. In this case the arrival time of additional appliances is not as critical in terms of surviving the fire. This is because the first appliance is already intervening at the incident and the impact that any additional support could have would not be as significant.

Such an experiment could be used to test proposals for boosting the capacity of swifter arrival times of the first appliance by means of surrendering capacity for arrival times of additional support. In practice, this would mean increasing the location spread of appliances. Stations with 2 or 3 appliances could be reduced to 1 or 2 and new station locations housing single appliances established. This suggestion would require further analysis including a cost-benefit study to weigh up the cost of maintenance of additional stations against the benefit of reduced risk. The additional stations could potentially be smaller with minimalistic content designed purely as a garage for a single appliance thus having lower running costs.

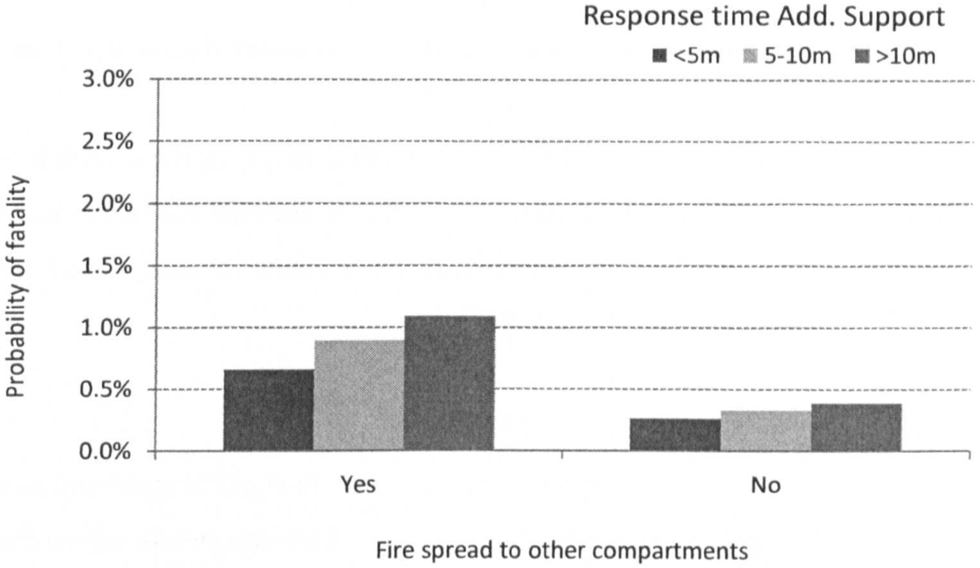


Figure 6.6. Effect of fire spread into other compartments and response time Additional support on posterior probabilities of the node "State of the occupant fire stage 3" [state: Dead].

Case 2 – Smoke alarm effect upon the probability of fatality and the human cost of fire

With the three main model parts now fully integrated the influence of parameters at the initial stage of the fire can be used to measure those at an advanced stage; importantly, the effect of these parameters can now be measured in economic terms.

This case demonstrates how the model can be used for undertaking a simple cost-benefit analysis. The probability of fatality (Figure 6.7 left y-axis, bars) during a dwelling fire has been plotted together with the human cost in £ (Figure 6.7 right y-axis, points/line) as a function of the type of smoke alarm installed in the dwelling; note that the human cost quantifies injuries as well as fatalities. It is evident that not having a smoke alarm results in a higher probability of fatality and human cost, a fact already known. However, the model can now be used to assess if it would be worthwhile investing in installing a particular type of smoke alarm within all dwellings in England. The calculation for the *combined* type of smoke alarm is as follows:

BENEFIT

Human cost difference between *no alarm* and *combined* alarm per fire from model

= 37,128 – 27,326 = £9,802

Number of dwelling fires (mean 2008-2010) = 37,017

Human cost difference between *no alarm* and *combined* alarm for all fires (*i.e.* the benefit should all dwellings have combined smoke alarm)

= 9,802 x 37,017 = £362,840,634

COST

Number of dwellings in England = 22,200,000
Combined smoke alarm retail cost = £13.14 (Amazon, June 2012)
Combined smoke alarm cost to FRS = £7.88 (assuming 40% discount)
Installation cost per alarm = £5
Cost of combined smoke alarm installed = 7.88 + 5 = £12.88
Cost of installing in all dwellings = 22,200,000 x 12.88 = £286,024,800

COST-BENEFIT

It would cost £286,024,800 to install combined smoke alarms in all dwellings in England and the benefit would be a reduction of risk in terms of human life of £362,840,634. This would mean society would be better off by *circa* 363 – 286 = £77 million.

The above calculation has been repeated for all types of smoke alarms with the result provided in Table 6.4. Each smoke alarm has a different impact upon risk and hence benefit due to their varying response times as a function of the type of fire. The cost of all the alarms has been obtained from the online retailer Amazon on the same day, for 1 year alarms, and for the same brand of alarm. A 40% reduction has been applied in costing to FRS based on expert opinion. However prices can only be taken as very approximate since market conditions, sales and so forth will not allow precise comparisons to be made. The calculations and results are only a demonstration of how the model results can be used to assist a cost-benefit exercise. In Table 6.4 the best option alarm would be *optical,* with *ionisation* and *combined* in second and third place respectively. The combined alarm, capable of detecting both flaming and smouldering fires quickly, is best for reducing risk but its higher cost would make it the least favoured option.

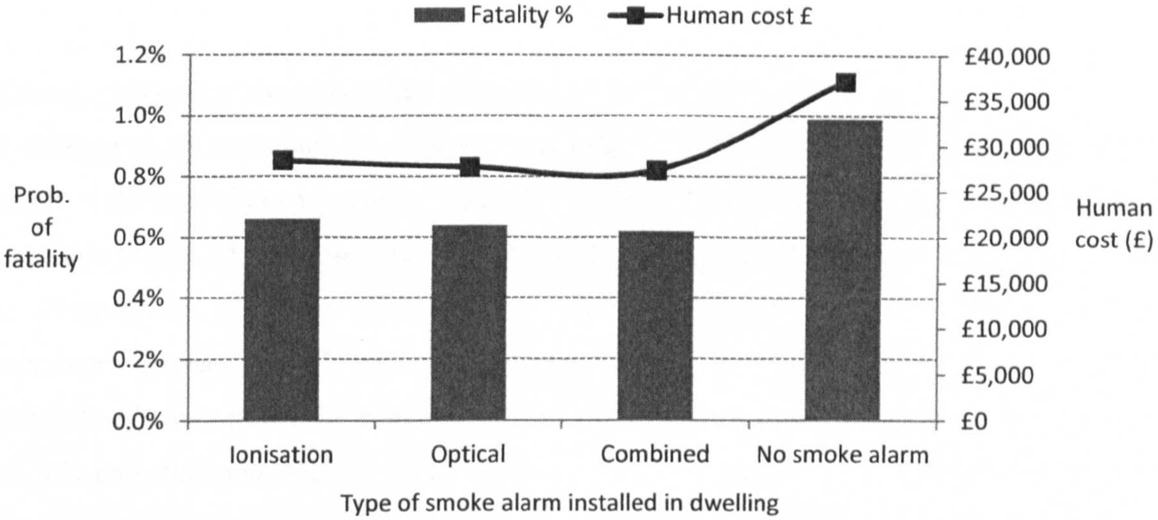


Figure 6.7. Probability of death and human cost of fire as a function of type of smoke alarm installed in dwelling.

Table 6.4. Cost-benefit to society of installing smoke alarms in all dwellings in England by type of alarm

	Smoke alarm type		
	Ionisation	Optical	Combined
Benefit	£322,492,104	£350,254,854	£362,840,634
Smoke alarm cost to FRS	£5.40	£5.56	£7.88
Installation cost	£5.00	£5.00	£5.00
Installed SkAl cost in all dwellings	£230,880,000	£234,343,200	£286,024,800
Cost-benefit	£91,612,104	£115,911,654	£76,815,834
Best option	2	1	3

This hypothetical argument for the installation of smoke alarms would also need to consider other factors besides cost and benefit. For instance, many people surprisingly do not like having a smoke alarm around and have in the past refused firefighters from entering their homes to install free alarms. Other people are known to tamper with the alarms, paint over them, or even take the battery out to use elsewhere. These issues would affect the benefit that is theoretically displayed in Table 6.4 leading to a requirement for further modelling of human behaviour with regards to the acceptance of smoke alarms.

Case 3 – FRS response time effect upon cost of consequences

This case study examines the effect of response time of the first appliance measured in terms of the cost of consequences. Figure 6.8 presents the results by means of a bar chart for the three groups of response times broken down into human and property costs in £. It can be observed that as response time becomes greater so do the cost of the consequences. The increment between the 2nd and 1st time band is 28% and 3rd and 1st 43%. This is another example of how the results from the model can be used to assist in a cost-benefit exercise. In this case the potential of faster response could be measured up against the benefits derived from the results below. Data on the cost to supply and maintain additional appliances to improve travel time was not available in sufficient detail to undertake such an exercise. Information required covers the cost of new appliances, operating costs (fuel, maintenance, insurance, *etc.*) over the durable lifetime, garaging costs, station additional maintenance, crew numbers, individual salaries depending upon experience, and so forth.

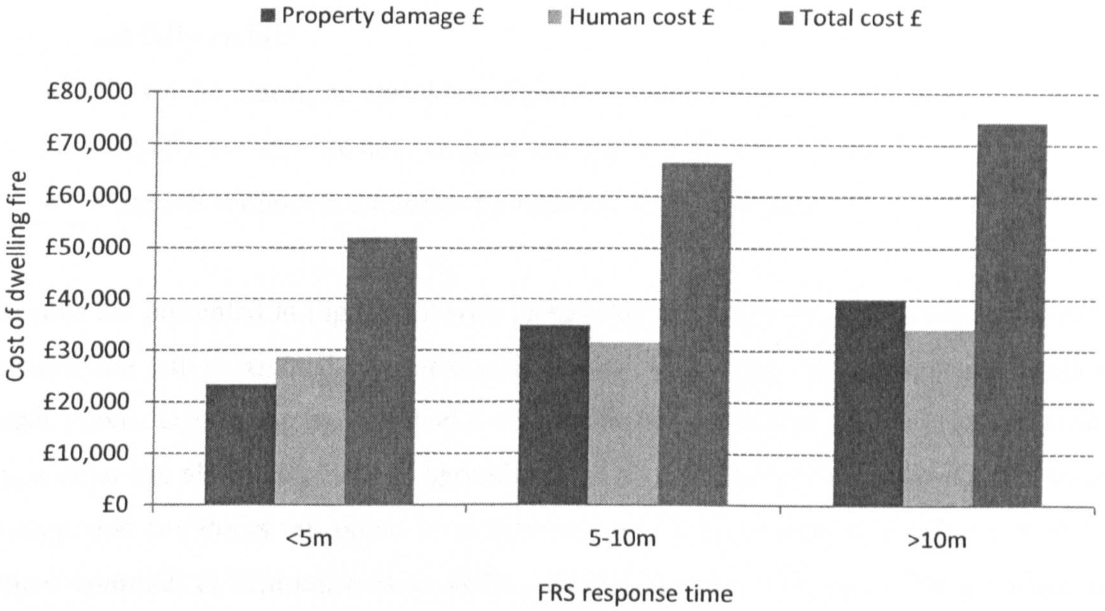


Figure 6.8. Cost of dwelling fire consequences as a function of response time of App. 1.

<u>Case 4 – Multiple circumstances effect upon probability of fatality and human cost £</u>

The final case study presents a selection of nine common dwelling fire circumstances. Their effects upon the chance of survival of the occupant, the cost of consequences in terms of people and the cost in terms of damage to property, are all examined; this allows comparisons to be made between common fire situations with the aim of identifying where the most pressing issues lie. The conditions considered are:

- The presence of any type of smoke alarm
- No smoke alarm
- Any smoke alarm plus a sprinkler system
- No smoke alarm, no sprinkler, and nighttime
- No smoke alarm, no sprinkler, nighttime, occupant asleep, fire door shut
- Any smoke alarm, no sprinkler, nighttime, occupant asleep, fire door open
- No smoke alarm, no sprinkler, nighttime, occupant asleep, fire door open

- No smoke alarm, no sprinkler, nighttime, occupant asleep, fire door shut, occupant not fully mobile
- No smoke alarm, no sprinkler, nighttime, occupant asleep, fire door shut, occupant not fully mobile, fire not extinguished between fire stage 1 and 2
- Materials without fire retardant properties, fire doors open

Results are presented in Figure 6.9 with probability of fatality shown by bars and measured against the left y-axis and cost of consequences by markers / lines measured against the right y-axis. One of the most typical dwelling fire circumstances occurs in homes with any type of smoke alarm installed, no sprinklers system, a nighttime situation with the occupant asleep, and fire doors left open. In such situations the probability of fatality is 0.98%. An equal common circumstance is as before except that there would not be a smoke alarm present in which case the probability of fatality rises by x 1.59 to 1.56%; the human cost is £49,985. People who are not fully mobile are also at a higher risk as shown by the third and second to right bars in Figure 6.9. In such situations the probability of fatality rises to 1.71% and 2.06% (human cost £54,589 and £64,311) irrespective of whether the fire is extinguished at an early stage or not. In any case it is unlikely that a person with limited mobility would attempt to extinguish a fire. This is why homes with such individuals should be highlighted as high risk and have if possible some sort of automatic alarm system connected to MACC or a private fire security officer. The various other results provided in Figure 6.9 are given to demonstrate the array of circumstances that can be investigated with the model. These can be combined further with response times, human actions, geographic location, and various other characteristics if desired.

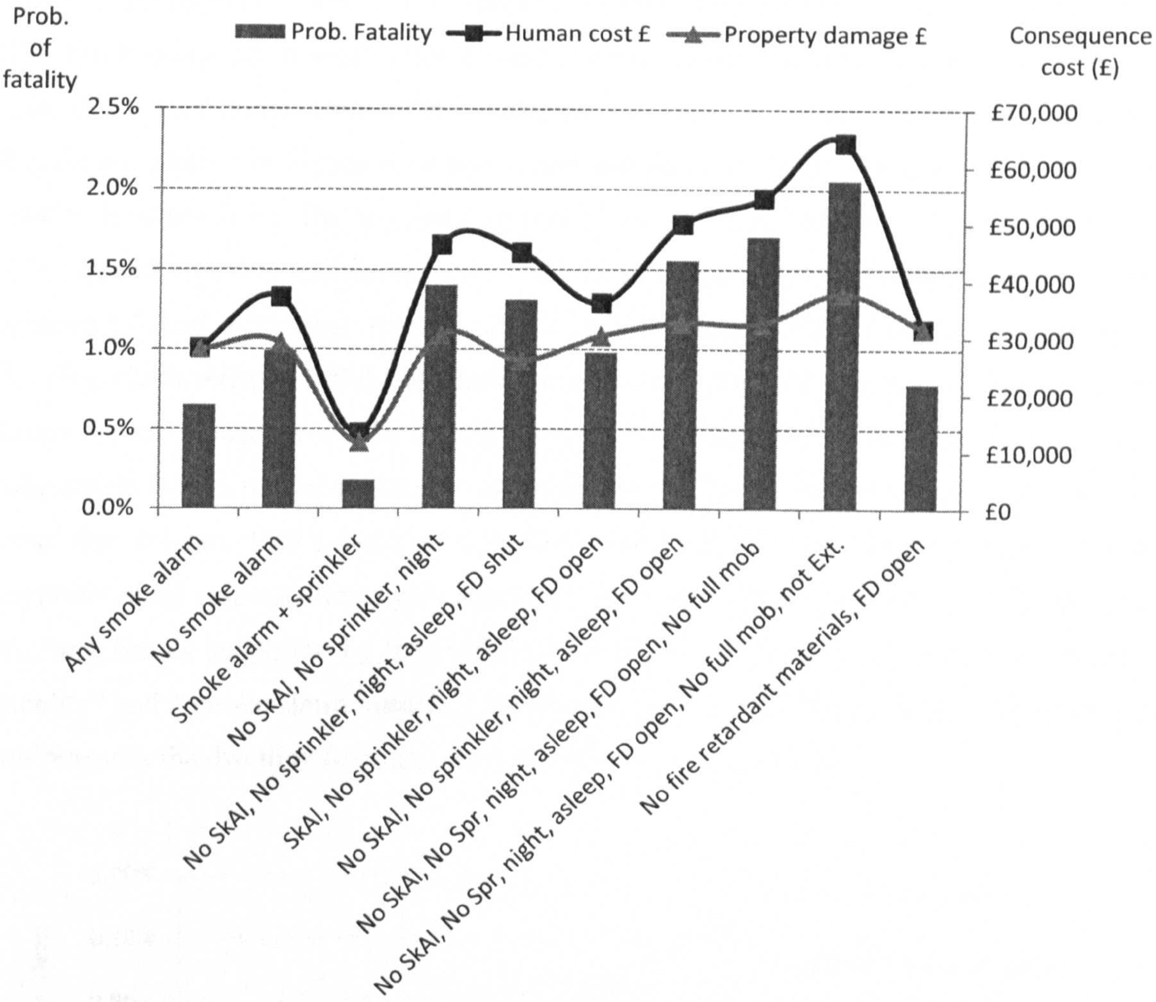


Figure 6.9. Cost of dwelling fire consequences based upon a variety of common dwelling fire circumstances.

6.6 SENSITIVITY ANALYSIS

The fundamentals and reasons for undertaking SA are discussed in Chapter 4, section 4.8. SA was conducted for part III of the model focusing on the output node “State of the occupant fire stage 3”. This node is also one of the main outputs for the entire model so the analysis conducted included nodes from parts I and II of the model. Changes were made in increasing and decreasing steps of 5% to the nodes “Appliance 1 at scene” (part II), "Additional support at scene", "Fire spread to other compartments", "Smoke lethality" (part II), "Firefighting equipment" (part II) and "Smoke alarm installed" (part I). The impact upon the output node "State of the occupant fire stage 3" [state: Dead] was measured. Results are plotted in Figure 6.10 and values are given in Table 6.5 arranged in order of most to least sensitive. The key node for part III of the model in terms of human fatality is "Fire spread to other compartments". This is followed by the response times of FRS appliance 1 and additional support. There is little control FRS's could exercise upon dwelling characteristics which influence spread of fire; the principal way to control a fire during the early stages would be for a dwelling to have a sprinkler system and to ensure that combustion is kept to a minimum by increasing the proportion of fire retardant materials to those that are not. FRS's however can have a big impact upon response times; this is important since response times play a big role in influencing the probability of fatality in a dwelling fire as supported by this sensitivity analysis. Other parameters such as "Smoke lethality" and "Smoke alarm installed" are also important whilst the presence of firefighting equipment in the dwelling (extinguishers, fire blankets, *etc.*) less so.

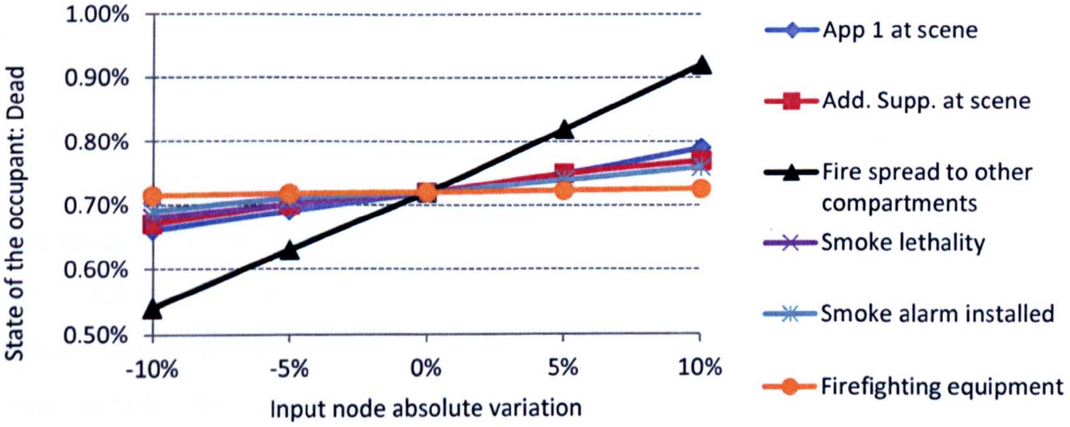


Figure 6.10. Sensitivity functions of five nodes from part I to part III on "State of the occupant fire stage 3" [state: Dead].

Table 6.5. Sensitivity values for five nodes from part I to part III acting upon the output node "State of the occupant fire stage 3" state [Dead]. Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Fire spread to other compartments	0.01933
Appliance 1 at scene	0.00633
Additional support at scene	0.00500
Smoke lethality	0.00400
Smoke alarm installed	0.00360
Firefighting equipment	0.00040

6.7 FURTHER DEVELOPMENTS OF THE MODEL: VARIABLE OCCUPANCY

As pointed out earlier one of the advantages of BNs is that they can be expanded as more knowledge is gathered about a system. Chapters 4 and 5 have put forward various suggestions such as giving the model a social aspect, addressing human disabilities / impairments, adding fire frequency information, and inclusion of discrete decision making nodes. The next big step in the development of this model is to produce a variable occupancy version. In reality the single occupancy BN is limited in application since the majority of dwellings have variable occupancy. The posterior probabilities and results of the current model compare well with statistics, particularly in terms of modelling the impact of response times and dwelling characteristics upon human and property consequences. However, aspects of human behaviour such as in-house firefighting, evacuation, *etc.*, would be influenced by the number of occupants in a dwelling and this is where the model could be improved. Chances of human reaction and swifter 999 calls would be greater in multiple occupancy homes however exposure to fire would be greater. Empty dwellings would only have a human cost if they spread to neighbouring dwellings, but the delay in alerting emergency services would result in greater property damage. These are aspects that need investigating.

A variable occupancy version of parts I to III has been developed although CPTs still required additional work. Nevertheless the networks are presented to demonstrate how the model has been further developed.

6.7.1 Part I variable occupancy

One additional node has been added and connections made as indicated in Figure 6.11 in order to convert part I of the model into a multiple occupancy version. The node description is as follows:

1. Number of occupants [states: 0, 1, 2 to 4, >4] – This parentless chance node represents the number of people within the dwelling at the time of fire. Data has been compiled from Communities and Local Government (2010b and 2010c), The Guardian (2012) and the Office for National Statistics (2012).

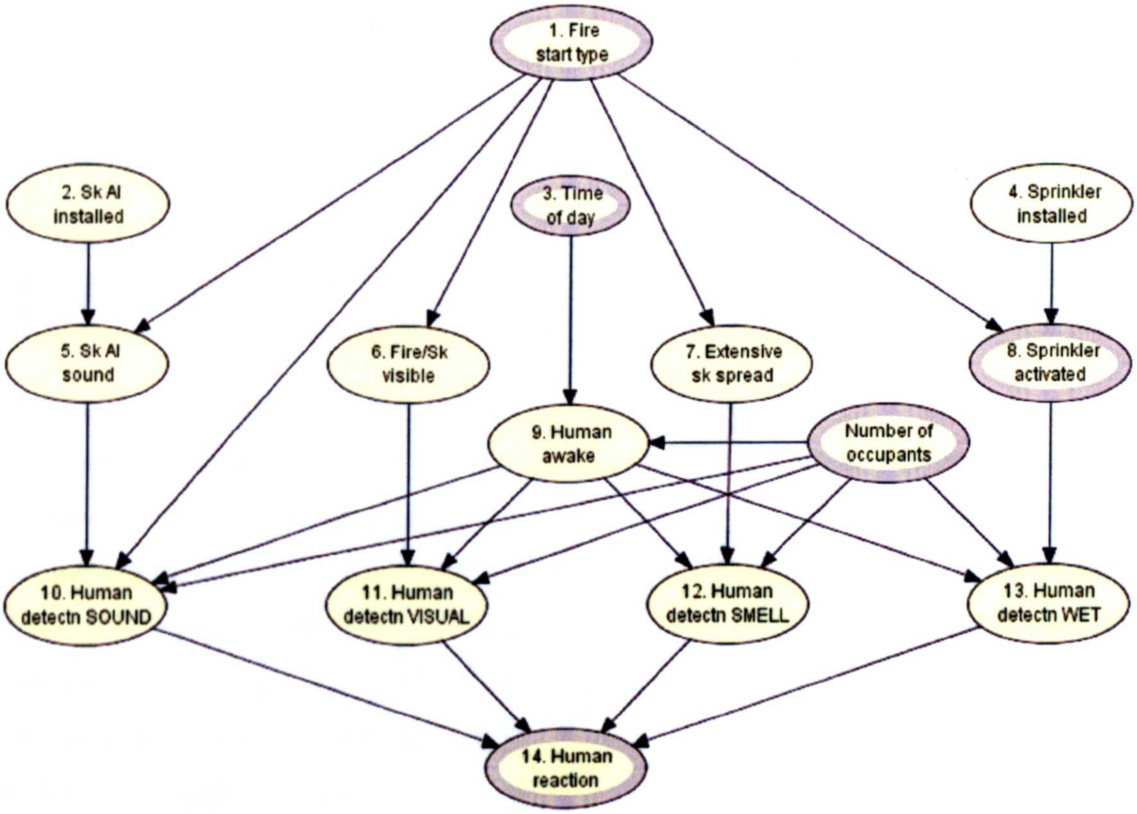


Figure 6.11. Variable occupancy version of BN Model Part I.

Prior and posterior probabilities have been noted for human reaction with different levels of occupancy and are provided in Table 6.6. The probability from the single occupancy version of the model has also been included for comparison. It can be noted that both prior probabilities are very close indicating that the current single occupancy version of the model differs little from the variable occupancy version. This indicates that the single occupancy version is performing well in terms of final model outputs. As noted earlier, a fully integrated variable occupancy version would however permit comparing situations with different numbers of people; this would allow for example analysis of risk in areas prone to overcrowding.

Table 6.6. Prior probabilities for Human reaction.

Part I version	Number of occupants	Probability of human reaction
Single occupancy	1	79.04 (prior probability)
Variable occupancy	unknown	80.87 (prior probability)
Variable occupancy	0	0
Variable occupancy	1	79.04
Variable occupancy	2 to 4	85.95
Variable occupancy	>4	91.10

6.7.1.1 Case study – Number of occupants and human reaction

A case study is presented to demonstrate how the variable occupancy version of the model functions. In the example the probability of human reaction to a fire is examined in terms of the time of day, the smoke alarm availability and the number of occupants in the dwelling. Figure 6.12 provides the results through a graph with three lines in which each line represents the probability of human reaction based upon different number of occupants; four fire scenarios are outlined along the x-axis. From the graph it can be seen that the greater the number of occupants the higher the probability of human reaction, under all circumstances. What is notable from these results is that the difference between low and high levels of occupancy is greater in nighttime situations, and even more so when there is an absence of smoke alarms. During a nighttime fire without a smoke alarm, a single occupancy situation would result in a 49.7% chance of human reaction; however if there were four occupants this figure would rise to 77.3%. The lower probabilities of reaction for single occupancy homes are actually more critical in practice since many of these situations involve individuals who are elderly, less mobile and hence highly vulnerable. Furthermore single parent homes are often considered or classed as single occupancy (Smith et al., 2008); very young children would not contribute towards an increase in human reaction, but would rather present additional problems for the parent.

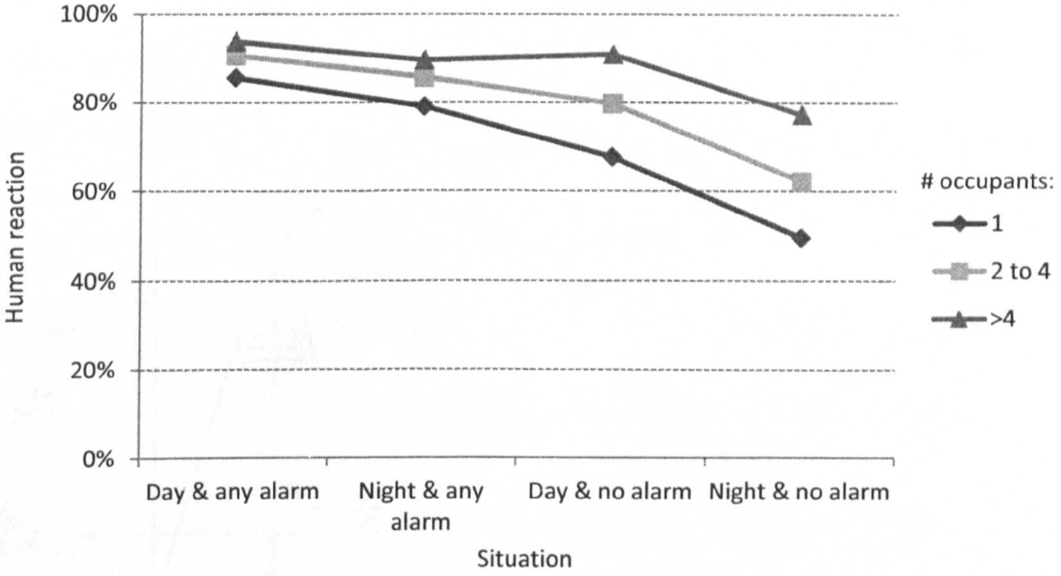


Figure 6.12. Posterior probabilities for "Human reaction" with evidence inserted for "Time of day", "Smoke alarm installed", and "Number of occupants".

6.7.2 Part II variable occupancy

The variable occupancy version of part II of the network includes six new nodes; these are listed below but no explanation is given since information for the CPTs is incomplete; none of the new parameters are root nodes. Figure 6.13 presents the network.

1. Alert others [states: Yes, No].
2. Evacuate others [states: Yes, No].
3. Group evacuation successful [states: Yes, No].
4. Seek shelter fire stage 2 [states: Yes, No].

5. Number of in-house firefighting [states: Yes, No].
6. Number of people to be rescued [states: 0, 1, 2 to 4, >4].

Also note that the node "Seek shelter" has been modified to "Seek shelter fire stage 1" [states: Yes, No].

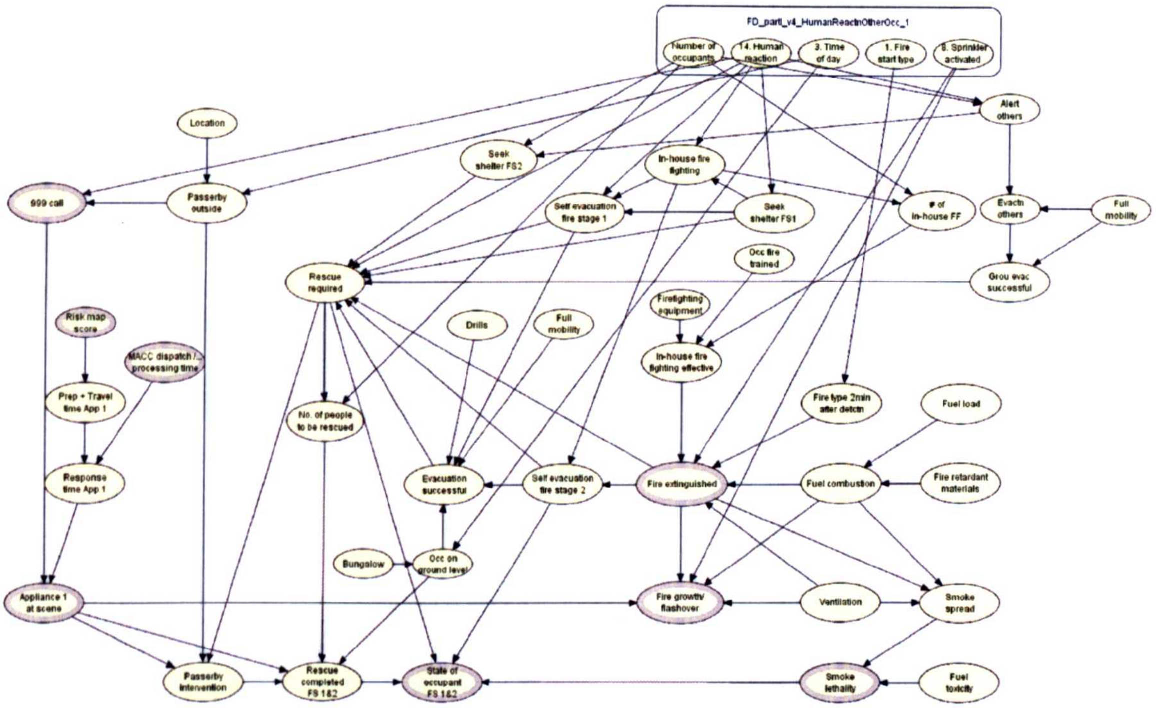


Figure 6.13. Variable occupancy version of BN Model Part II.

6.7.3 Part III variable occupancy

In the advanced fire situation multiple occupancy would influence the probability of a second rescue attempt being required. Part III of the model is now linked to the variable occupancy version of part I with the node "Number of occupants" featuring as a new transfer node. Figure 6.14 provides an idea of what the modified part III network might look like.

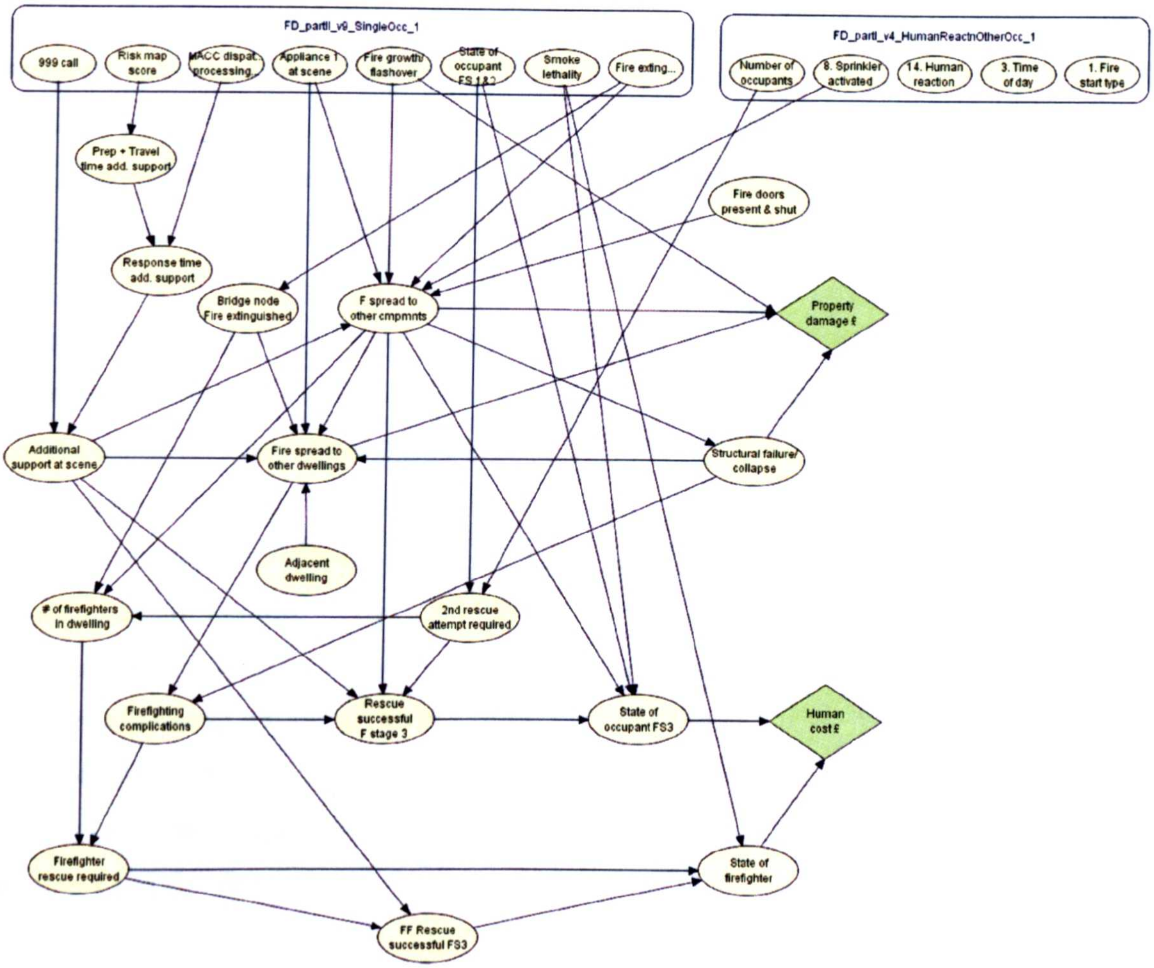


Figure 6.14. Variable occupancy version of BN Model Part III.

6.8 CONCLUSIONS AND BRIEF DISCUSSION

This chapter presents the last part of the core of the BN model designed to model dwelling fires. Part III addresses the advanced fire situation and consequences though a series of seventeen chance nodes and two utility nodes. These link up with parts I and II of the model through several transfer nodes which have a direct influence upon the development and spread of fires at an advanced stage. FRS intervention is represented through several time based nodes.

Four case studies have been conducted examining a variety of potential 'real world' situations; the case studies also demonstrate how the fully integrated model works and some potential uses. In case 1 the impact upon fatalities is assessed in terms of fire spread and FRS response time. It was noted that timely FRS intervention, in particular the arrival of appliance 1, is far more critical when the fire has spread beyond the room of origin.

In case 2 the model is used to examine the effect upon probability of fatality and the economic cost of consequences in terms of people. The results are used to demonstrate how a cost-benefit analysis could be undertaken in support of the nationwide installation of smoke alarms, highlighting which type of alarm would be the best cost-effective option. Case 3 assesses the effect of FRS response time solely upon the economic cost of consequences of the fire. This is achieved by modelling various levels of performance upon outcomes in terms of the human cost and damage to property in £. The final case study presents a series of common fire scenarios with the purpose of comparing the effect upon the probability of fatality and human cost. The dangers of nighttime fires without smoke alarms were once again highlighted as well as issues surrounding occupant mobility problems and fire doors.

The final part of the chapter presents further development of the complete model by way of turning it into a variable occupancy network. It was noted that at present the current model provides good results in line with statistics. FRS response times and dwelling characteristics can be modelled with some precision. Human behaviour however can become far more complex when many people are present in a dwelling fire. To address this matter, section 6.7 presents the model with additional nodes potentially capable of modelling some of these situations; a case study is developed with the variable occupancy version of part I of the model.

CHAPTER 7 – BAYESIAN NETWORK MODELLING FOR FIRE SAFETY ASSESSMENT: PART IV - FIRE RESPONSE TIME MODULE AND INTEGRATION WITH PARTS II & III

SUMMARY

This chapter presents the final part of the BN built to model the response time of FRS's as a function of the natural and man-made environment in which they have to operate. This network is set-up to be a module of the core three part model; this means that it can function independently from parts I to III and vice versa. The focus of this part of the network is upon response times of appliance 1 and additional support. Case studies are presented to determine what the most important parameters are and the degree of influence they exercise upon response time and risk to life. The 'risk-map' linked versions of parts II and III of the model delivered through Chapters 5 and 6 respectively are modified so that they connect with part IV; this is presented towards the end of this chapter.

7.1 INTRODUCTION

As discussed in earlier chapters the timely response of FRS's to fire incidents is hugely important to minimising the risk to occupants and property. For this reason, assessing how FRS response time is itself influenced is a significant matter. It is possible to argue that travel time of appliances must be speedy regardless of circumstances; however, there are situations in which it is physically impossible or indeed dangerous to travel at high speeds. Upon this background, this chapter examines the issues that affect FRS response time and in turn overall risk from fire. A BN has been developed to address these matters and is presented as part IV of the model; this network links up with parts II and III as shown in Figure 7.1. In the diagram part IV (shaded grey) is shown to the left of the other model parts and is named the *fire response time module*. The network has been designed to either be used alone to study fire response times or to be incorporated into the rest of the model to assess risk. In order to link up with the rest of the model a slight modification has had to be made to parts II and III in which response time nodes are replaced with transfer / instance nodes for response time (see section 7.6). Part IV of the model incorporates parameters related to call/information processing time, crew preparation time, appliance travel time, and integrated response for both appliance 1 and additional support.

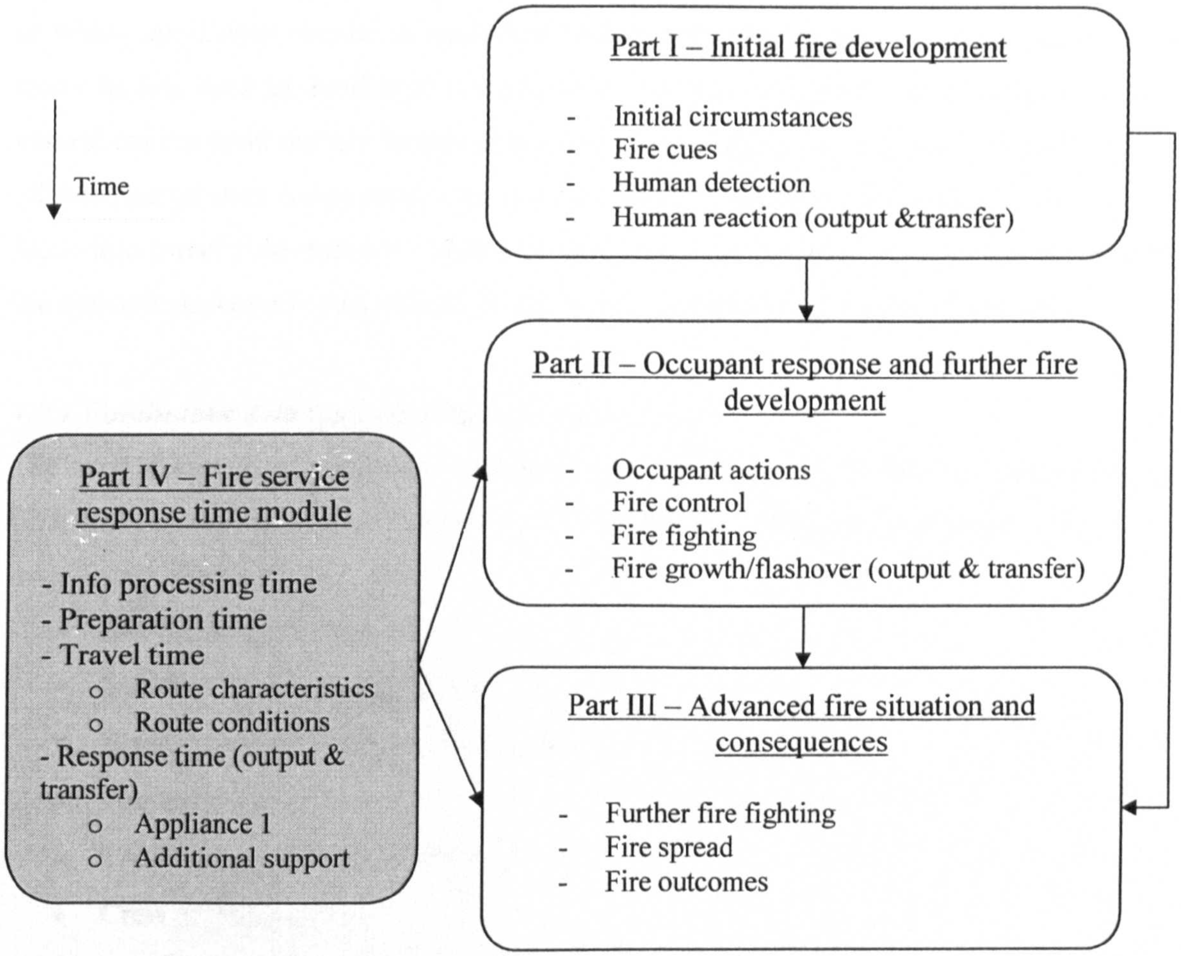


Figure 7.1. Flow chart of events within the complete BN model

The rest of this chapter delivers a detailed account of part IV of the BN (section 7.2), explains how data was compiled (section 7.3), develops several case studies (section 7.4), undertakes a sensitivity analysis (section 7.5), presents modifications for parts II and III of the network (section 7.6), and provides some brief conclusions and discussion (section 7.7).

7.2 PART IV OF THE MODEL – FIRE TIME RESPONSE MODULE

The fourth part of the network was built following the same procedure as for the other parts described in Chapter 4, section 4.3.1.1. The network has been structured so as to determine the response times for both appliance 1 and additional support; these are the focus and transfer nodes for this part of the model. The parameters that affect these two nodes are the same and for this reason part of the network has a symmetrical structure. The environment in which appliances operate is modelled. This is addressed from the perspective of man-made factors such as road works, traffic, crowds, *etc.*, and from the perspective of the natural environment namely month of the year, precipitation, ice, fog, *etc.* The influence of all these parameters congregates upon a node termed "Impact on travel time" which in turn feeds into travel time nodes for appliance and additional support. From this point forward the network structure is very similar for the two appliance measures of FRS response.

7.2.1 Continuous data represent through discrete nodes

The need to represent continuous parameters through discrete nodes has been explained in Chapter 5, section 5.2.2. Part IV of the model includes the following time based nodes:

- Impact on travel time
- Standard travel time appliance 1
- Standard travel time additional support
- Travel time appliance 1
- Travel time additional support
- Crew preparation time
- Preparation + travel time appliance 1
- Preparation + travel time additional support
- MACC dispatch / call processing time
- Response time appliance 1
- Response time additional support

7.2.2 Nodes and structure

Part IV of the BN consists of twenty nine chance nodes plus one transfer node "Time of day", from part I. The reasoning and assumptions behind each node are given below. Nodes have been grouped into *calendar nodes, weather effects, man-made effects, speed and travel time,* and *other time nodes.*

Calendar nodes:

1. Time of year [states: January, February, March, April, May, June, July, August, September, October, November, December] – This root node represents the month of a year. The reason for including this node is that it affects weather which in turn will impact upon travel time. Probabilities for each month were computed by dividing the number of days in the month by the number of days in a year.

Weather effects:

2. Air and ground frost [states: Yes, No] – This chance node represents the formation of frost at either air or ground level. Frost will form if temperatures drop below 0°C. Sometimes ground level temperature will have dropped below freezing but air temperature may be slightly above; this occurs for example at the beginning of a cold day. If a surface is wet, ice can form as long as either air or ground frost conditions are present. To complete the CPT for this node data for the weather station Ringway Manchester Airport was obtained from the UK Met Office for the years 1971 to 2000. Further details on how the data was compiled are provided in section 7.3. Conditional probabilities were set according to the parent nodes "Time of year" and "Time of day".
3. Ground ice / snow [states: Yes, No] – This chance node describes the presence of ice and/or snow on the road surface; note that 'black ice', a thin transparent layer of ice commonly referred to when describing frozen road conditions, is also encompassed within the word 'ice'. This node's conditional probabilities are set in relation to the state of the parent nodes "Precipitation" and "Air temperature on ground".

4. Dense fog [states: Yes, No] – This chance node represents the presence of dense fog at ground level. A dense fog will reduce visibility to less than a quarter of a mile (*circa.* 400 metres) (NOAA, 2012: North West Weathernet, 2012). The CPT for this node was compiled based on data for the weather stations Ringway Manchester Airport, Woodford, and Ness Gardens which are all within the North West of England. The data span from 1971 to 2011 and was obtained from the UK Met Office. Further details on how the CPT was compiled are provided in section 7.3. Conditional probabilities are set according to the node's parents "Time of year" and "Time of day".
5. Precipitation [states: Heavy, Light, None] – This chance node describes the fall of water in any form from the sky to the ground. The state of precipitation [light] is considered when the mean monthly hourly amount of rain is below the mean yearly hourly amount of rain, whilst [heavy] is considered to be above this value. According to the UK Met Office (2009) any value above 4mm / hr is considered heavy rain whilst Alhassan and Ben-Edigbe (2011) put the limit at 2.5mm. Data for this node was obtained from the weather station Ringway Manchester Airport from the UK Met Office for the years 1971 to 2000. Further details on how the CPT was compiled are provided in section 7.3. Conditional probabilities are set according to the node's sole parent "Time of year".

Man-made effects:

6. Road works [states: Yes, No] – This parentless chance node represents the state of roads being partially or fully closed off due to road works; this is measured in terms of percentage of lane availability. Planned work makes up about 2% of road disruption while a further 2 to 3% is due to unplanned emergency work. Data for this node was obtained from personal communication with an expert from the Highways Agency (email, September, 2011).
7. Major public event [states: Yes, No] – This root node represents large public events such as concerts, festivals, protests, sports events, charity events and so forth which involve crowds gathering on streets. Past examples on Merseyside include the

Matthew Street Festival, the Liverpool Marathon, the 2012 Sea Odyssey Giant's Parade, *etc.* Although such events typically only affect small areas of a city / town the disruption to passing traffic can be significant. Data for this node is a combination of the frequency of such events and the area potentially affected.

8. Crowd near roads [states: Yes, No] – This chance node represents the presence of large crowds near roads or attempting to cross them. Situations like these are typical during major public events and at certain peak congestion times during rush hour. The node's conditional probabilities are set in according to its parents "Major public event" and "Time of day".
9. Traffic congestion [states: Yes – heavy, Yes – slight, No] – This chance node describes the density of vehicles on roads. Information on congestion was obtained from Alhassan and Ben-Edigbe (2011) and Keay and Simmonds (2005). The node's conditional probabilities are set in line with its parent nodes "Time of day", "Road works", and "Major public event".

Speed and travel time:

10. Driving speed [states: More than 15% slower, Up to 15% slower, No effect] – This node describes how the driving speed is affected by weather. It is assumed that precipitation and dense fog affects the route as a whole; however ice / snow is often localized and hence would vary along the route with untreated roads being more affected. This has been taken into account when computing the conditional probabilities which are based upon the parent nodes "Precipitation", "Ground ice / snow" and "Dense fog".
11. Impact on travel time [states: -22.5% (<-5%), 0% (-5 to 5%), 15% (5 to 25%), 30% (>25%)] – This chance node represents the effect upon travel time as a percentage. Standard travel times will be set according to the response strategy of an FRS however actual travel times may vary because of everyday factors such as traffic and weather. Ideally this node would be represented by a continuous node but due to the difficulties discussed earlier in the project this is not possible. Consequently four states have been set, one representing faster travel, one neutral, and two resulting in

slower travel. The node's conditional probabilities are set according to its parent nodes "Driving speed", "Traffic congestion", and "Crowds near roads". The logic is that free-flow driving speed is affected by the weather but this can subsequently be impacted by physical barriers such as traffic and people; hence this node provides a combined measure of the impact upon travel time. When constructing the CPT it is assumed that once an appliance has to slow its driving speed by more than 15%, light traffic congestion and crowds near roads will have a negligible effect as the vehicle is already going slow. The prior probabilities of this node are such that there is no impact upon travel time. Only when parent parameters begin to change is there an effect upon travel time via this node.

12. Type of appliance 1 [states: Appliance pump, Small fire unit, Motorbike] – This root node represents the type of appliance deployed by the FRS. In this research it is assumed that an appliance pump is sent to all incidents in line with current strategy. However, in the past other appliances have been considered by MFRS such as the small fire unit and even a motorbike. This node is included in the network to demonstrate how the type of appliance deployed can affect standard travel time.
13. Type of additional support [states: Appliance pump, small fire unit, motorbike] – This root node is identical to the previous one except it represents the type of additional support.

Note on nodes 14 to 19: These nodes are merely symbolic within the network and they are not incorporated into the modelling. Their inclusion is to illustrate how they can affect the establishment of standard travel times which may be developed in future work. The nodes are listed but not explained.

14. Distance appliance 1 [states: band A, band B]
15. Distance additional support [states: band A, band B]
16. Number of major road crossings location 1 [states: range 1, range 2]
17. Number of major road crossing location 2 [states: range 1, range 2]
18. Built-up area location 1 [states: Yes, No]
19. Built-up area location 2 [states: Yes, No]

20. Standard travel time appliance 1: [states: <5m, 5 to 10m, >10m] – This chance node represents the standard travel time component of preparation plus travel time as set by the response standards of MFRS for appliance 1. Its conditional probabilities are set according the parent nodes "Type of appliance 1", "Distance appliance 1", "Number of major crossings location 1" and "Built-up location 1".
21. Standard travel time additional support [states: <5m, 5 to 10m, >10m] – This chance node is similar to the previous one except that it represents additional support. The key difference is that it has as an extra parent node "Standard travel time appliance 1" since additional support cannot arrive before the first appliance. The other parent nodes are "Type of additional support", "Distance additional support", "Number of major crossings location 2" and "Built-up location 2".
22. Travel time appliance 1 [states: <5m, 5 to 10m, >10m] – This chance node represents the actual travel time of appliance 1. Prior probabilities are the same as for "Standard travel time appliance 1". Only when variations to "Impact upon travel time" occur will the actual travel time vary. Its conditional probabilities are set according to its parent nodes "Standard travel time appliance 1" and "Impact upon travel time".
23. Travel time additional support [states: <5m, 5 to 10m, >10m] – This chance node is identical to the previous one except it represents additional support.

Other time nodes:

24. Crew preparation time [states: 0m (mobile), 1m (0.75 – 1.25), 1.5m (1.25 – 1.75), 2m (>1.75)] – This parentless chance node represents the time from when fire crews are alerted of the incident to the moment when they begin the journey to the location. On about 10% of occasions fire crews are already mobile on an appliance undertaking non-emergency work; in such cases case crew preparation time is zero. For the other states a suitable time within a range has been selected. Data for this node was compiled from a questionnaire sent to fire crews (see Appendix 11) and from personal discussion with experts.

25. Preparation plus travel time appliance 1 [states: <5m, 5 to 10m, >10m] – This chance node is the aggregation of crew preparation time and appliance 1 travel time. Its conditional probabilities are according to its parent nodes "Travel time" and "Crew preparation time".
26. Preparation plus travel time additional support [states: <5m, 5 to 10m, >10m] – This chance node is identical to the previous node except it represents additional support.
27. MACC dispatch / call processing time [states: 0.75 (<1) minutes, 1.5 (1 to 2) minutes, 2.5 (>2) minutes] – This parentless chance node is identical to the one described in Chapter 5, section 5.2.4. It has not been included as a transfer node since part IV of the model is independent to the 'risk-map' linked version of part II of the model where this node first features.
28. Response time appliance 1 [states: <5m, 5 to 10m, >10m] – Similarly to the previous node this chance node is identical to the one described in Chapter 5, section 5.2.4 and has not been included as a transfer node for the same reason.
29. Response time additional support [states: <5m, 5 to 10m, >10m] – This chance node is identical to the previous one except it represents additional support.

Figure 7.2 presents part IV of the BN following a top to bottom ordering of nodes. Natural environment nodes are located towards the top left while man-made environment nodes towards the top right. Further down the network on the left side are appliance 1 nodes with additional support nodes on the right. The focus and transfer nodes are at the bottom.

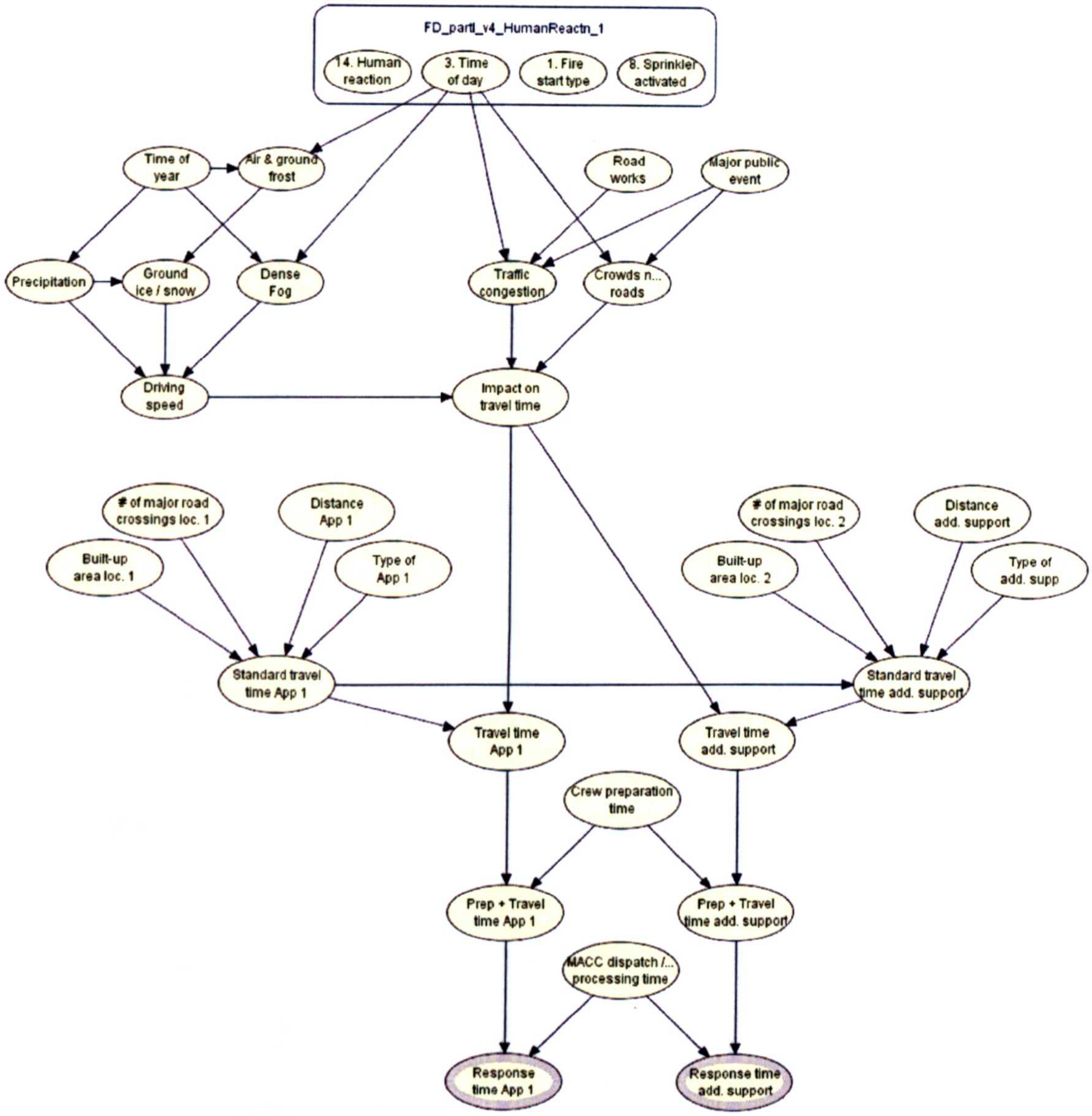


Figure 7.2. Part IV of the BN model: Fire response time module.

7.2.3 Model d-separation

The d-separation test has been conducted for both of the focus nodes to check that all parameters within the network are relevant to the outputs. Figures 7.3 and 7.4 provide the results for the focus nodes "Response time appliance 1" and "Response time additional support" respectively. There are irrelevant nodes for "Response time appliance 1" marked with a red X, but these are relevant for "Response time additional support" and hence should not be excluded from the network. In figure 7.3 the additional support travel time nodes are also *d-separated* because they are child nodes of other nodes which diverge onto the path towards the focus node. Further d-separation checks have been conducted for other part IV nodes the ensure network relevance of respective influencing nodes.

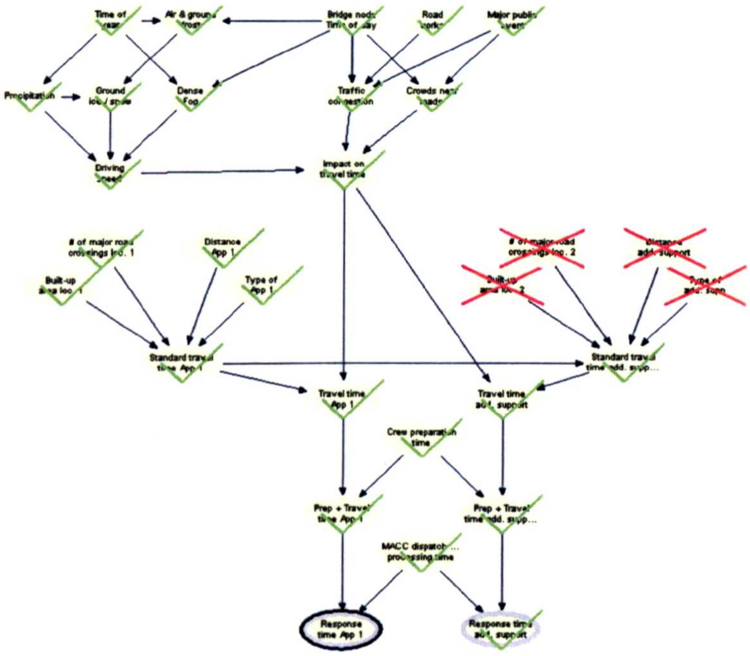


Figure 7.3. D-separation test for the focus node "Response time appliance 1".

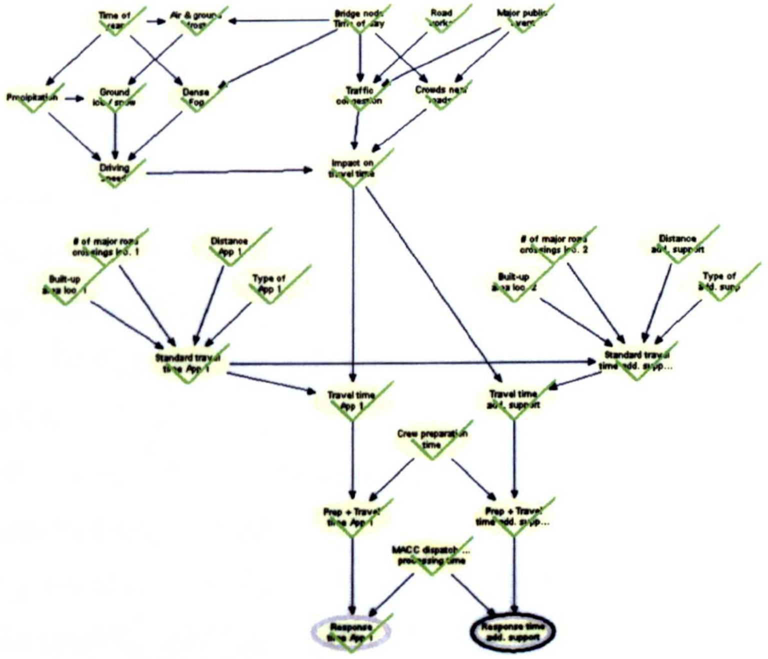


Figure 7.4. D-separation test for the focus node "Response time additional support".

7.3 NODE CONNECTIONS AND DATA FOR THE BN MODEL

7.3.1 Node connections and further details on construction of CPTs

Part IV of the network consists of twenty nine nodes connected via serial, diverging, and converging *arcs*. A variety of sources were once again consulted to consolidate meaningful data to build CPTs. Expert opinion gathered via personal communication and through a questionnaire was a major contributor. Knowledge and data were also sourced from the UK Met Office, the Highway Agency, and various pieces of literature. In particular research into traffic and the effect of weather was reviewed from Alhassan and Ben-Edigbe (2011), El Faouzi *et al.* (2010), SWOV (2009), Keay and Simmonds (2005), and Golob and Recker (2003).

Constructing data to model the effect of certain combinations of parent nodes upon a child was undertaken applying the Noisy-OR gate (described in Chapter 4 section 4.4.2), for example for the node "Traffic congestion". A variety of assumptions have also been applied based on expert knowledge and literature explained where applicable in section 7.2.2.

For the weather nodes "Air / ground frost", "Dense fog" and "Precipitation", data was obtained from the UK Met Office for the North West region from meteorological stations near sea level and in or close to conurbation areas so as to be representative of the majority of areas in which FRS's operate. For these stations daily data was averaged for each month and subsequently for the period of years available. If more than one weather station data set was available, the average was taken for all weather stations. The probability of the weather condition during each month was then computed by dividing the monthly figure by the annual total. The following was then undertaken:

- Precipitation: The mean amount of rain in each hour in which it rained was computed. The figures were averaged. Any value above this average was considered [heavy] and anything below [light].
- Dense fog and frost: These are measured by the number of days in the month during which the conditions are present. To compute the probability within a month the value was divided by the number of days in that month. Then, because these

conditions are far more likely to occur during the night, a 40% increase was applied in setting the nighttime probability and a 40% decrease applied for daytime.

7.3.2 Questionnaire

A questionnaire was used in this part of the research to gather expert opinion from active firefighters. The information required related to fire crew preparation times and travel time to an incident. In particular questions were asked about weather, traffic, and crowds. One question was open ended so that the respondent could provide further opinions regarding travel time. The questionnaire is included as Appendix 11.

The questionnaire was sent to a total of twelve firefighters from Merseyside of whom three replied with some very useful information. In addition two experts were consulted in person regarding some of the questions to improve the range of opinions. When compiling the data, one expert was given a higher weighting than the firefighters since that person had research experience but also had been a firefighter. The data collected was used in constructing the CPTs for the nodes "Driving speed", "Impact on travel time" and "Crew preparation time". The node "MACC dispatch / call processing time" was also based on a questionnaire and expert opinion discussed in Chapter 5.

7.3.3 Summary of node data content

A summary of all nodes contained within part IV of the network is given in Table 7.1. Information is provided on the number of states for each node, the number of parent nodes, the number of permutations in the probability table, and the type of source of information. Specific sources of literature are not named in the table but referenced elsewhere in this Chapter where relevant (see sections 7.2.2 and 7.3.1). The nodes in the table are grouped according to the themes established in section 7.2.2. Note that all the CPTs are provided in Appendix 12.

Table 7.1. Probability table details for each node and origin of data for part IV.

Node #	Node name	# of states	# of parent nodes	# of permutations in Prob. Tab.	Probabilities compiled from	Subjective element
Transfer nodes from part I of the mode.						
3	Time of day	2	0	2	Literature	Yes
Part IV: Calendar and daytime nodes						
1	Time of year	12	0	12	Event logic	No
Part IV: Weather effects						
2	Air and ground frost	2	2	12	Literature	No
3	Ground ice / snow	2	0	3	Exp. op., literature	Yes
4	Dense fog	2	2	48	Literature	No
5	Precipitation	3	1	36	Literature	No
Part IV: Man-made effects						
6	Road works	2	0	2	Exp. op., literature	Yes
7	Major public event	2	0	2	Exp. op., literature	Yes
8	Crowds near roads	2	2	8	Exp. op., literature	Yes
9	Traffic congestion	3	3	24	Exp. op., literature	Yes
Part IV: Speed and travel time						
10	Driving speed	3	3	36	Exp. op., literature	Yes
11	Impact on travel time	4	3	72	Exp. op., literature	Yes
12	Type of appliance 1	3	0	3	MFRS	No
13	Type of additional support	3	0	3	MFRS	No
14	Distance appliance 1	2	0	2	unavailable (50/50)	n/a
15	Distance additional support	2	0	2	unavailable (50/50)	n/a
16	# of major road crossings loc.1	2	0	2	unavailable (50/50)	n/a
17	# of major road crossings loc.2	2	0	2	unavailable (50/50)	n/a
18	Built-up area location 1	2	0	2	unavailable (50/50)	n/a
19	Built-up area location 2	2	0	2	unavailable (50/50)	n/a
20	Standard travel time App 1	3	4	72	MFRS	No
21	Standard travel time Add. Supp.	3	5	216	MFRS	No
22	Travel time appliance 1	3	2	36	MFRS, exp. op.	Yes
23	Travel time additional support	3	2	36	MFRS, exp. op.	Yes
Part IV: Other time nodes						
24	Crew preparation time	4	0	4	Expert opinion	Yes
25	Prep. + travel time appliance 1	3	2	36	MFRS, see App 7	No
26	Prep. + travel time add suppt.	3	2	36	MFRS, see App 7	No
27	MACC dispatch / call prcess. T	3	0	3	Expert opinion	Yes
28	Response time appliance 1	3	2	27	MFRS, see App 7	No
29	Response time add. support	3	2	27	MFRS, see App 7	No

7.4 MODEL PART IV CASE STUDIES

This section presents several case studies designed to show how part IV of the model can work as a stand-alone network to analyse FRS response time, but also how it works as a component part to the whole BN model in assessing risk. FRS response time to fire incidents has a big impact upon the consequences; however it is not always possible for an appliance to arrive within the intended time. At MFRS response standards are achieved on about 90% of occasions. Part IV of the model can prove useful for analysing why response time targets are missed for 10% of incidents. This may help propose a solution to some of the issues.

In this instance the case studies formulated are geared towards analysing how numerous variables affect some of the principal outputs of this part of the model, namely the probabilities of fire growth, fatality and remaining trapped. The effect of the perceived most influential variables are combined and compared. For example, case 1 analyses how FRS response time and occupant actions affect the probability of remaining trapped. These factors have been documented to have a high impact upon the probability of the survival; in the case of response times refer to Fire Brigades Union (2012), Communities and Local Government (2009), and Mattsson and Juas (1997), while for occupant actions see Thompson (2011) and Meacham (1999). The model allows for a comparison of the combined effects of various occupant actions and different FRS response times to be made, which are presented within the results. In other case studies the effect of different safety configurations and common fire scenarios are compared. Each case study explains the interest in developing its respective results

Case 1 – Effect of month of the year upon travel time

Some of the factors which affect response times can be attributed to natural causes such as weather. It is therefore likely that FRS response time varies to a degree throughout the year. This case study examines the effect of the month of the year upon the travel time of appliance 1. Evidence was inserted into the model confirming the occurrence of each month and posterior probabilities for "Travel time appliance 1" were recorded. Results are provided in Figure 7.5 for the probability of arriving within 5 minutes (left y-axis) and between 5 to 10 minutes (right y-axis). It is evident that a trend exists in which appliance travel times are faster in summer, compared to winter. This can be explained by a higher probability of treacherous driving conditions during the colder months.

The issue now lies in whether the differences in travel times are significant. From the graph it can be seen that during the worst month travel time is about half a percent slower than during the best month. It would appear that there is therefore little impact when considering the month of the year as a whole. What may be more appropriate is to examine what happens on individual days of bad driving conditions and plan in accordance with this.

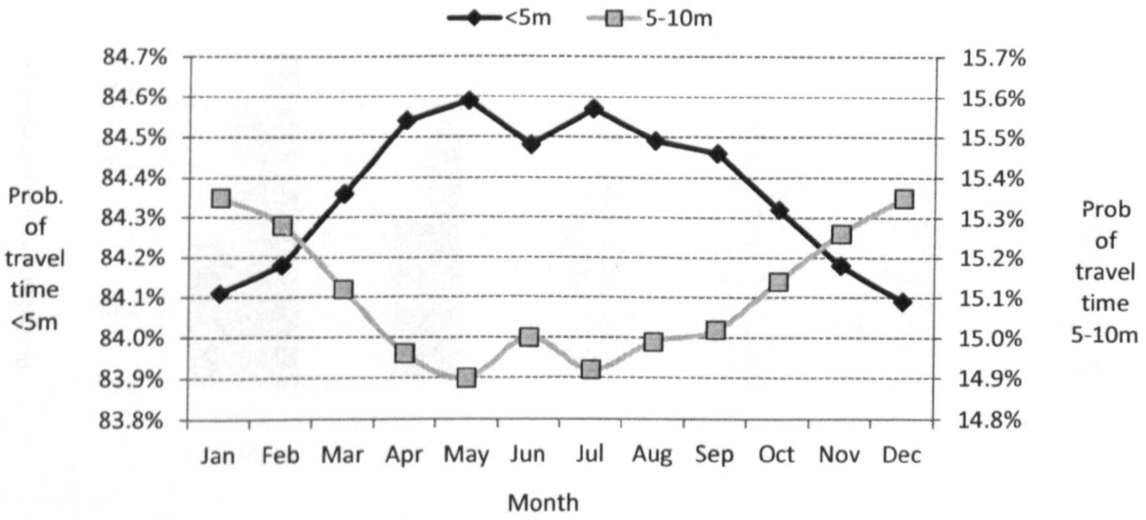


Figure 7.5. Probability of appliance 1 travel time within 5 minutes throughout the year.

Case 2 – Natural and man-made environment effects upon travel time

In this case study the effect that natural conditions (weather) and man-made conditions (traffic, crowds) have upon travel time of appliance 1 is examined. Figure 7.6 provides the results in terms of travel time within 5 minutes, according to six individual conditions (x-axis); the prior probability of travel time [<5m] is given by a black line so as to compare the posterior probabilities. Note that "Traffic congestion" and "Precipitation" have three states (see graph key) in which case three bars are shown for probabilities of travel time. In all cases when the condition is present the probability of fast travel decreases. The greatest effect occurs during conditions of heavy traffic congestion followed by heavy precipitation. The condition of time of day is also examined since it provides a useful insight into the combined effect of some of the other conditions. Its influence upon travel time is directed through a combination of fog, ice, traffic and crowds; the occurrence of the first two of these is reduced during daytime, whilst the last two are accentuated. The opposing changes to probabilities of occurrence seem to cancel each other out since there is little variation between day and night time conditions.

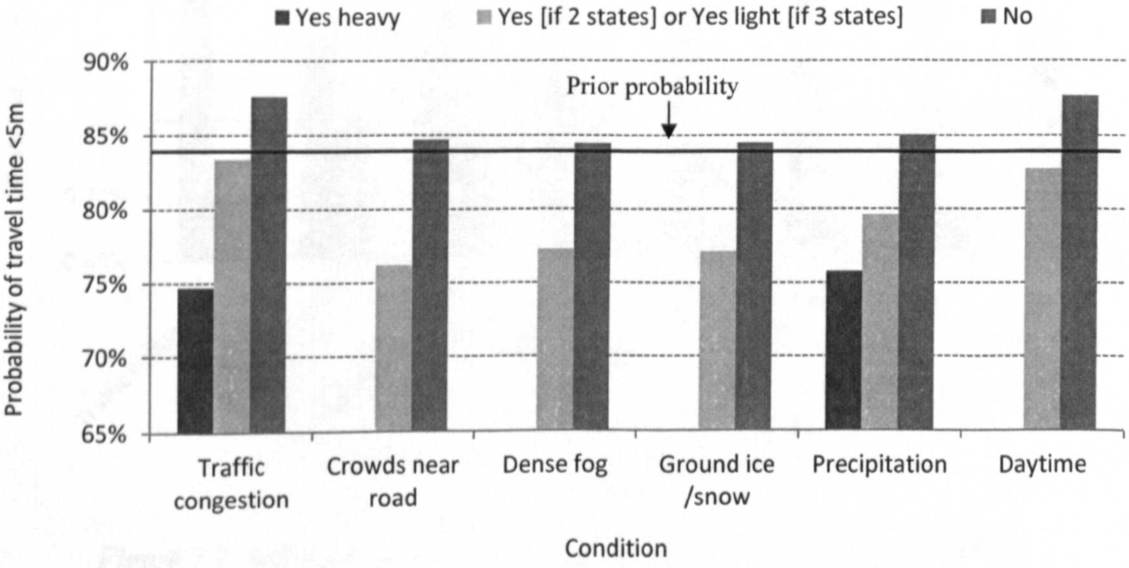


Figure 7.6. Influence of various conditions upon the probability of appliance 1 travel time within 5 minutes.

Case 3 – Natural and man-made environment effects upon the probability of fatality

The final case study sees part IV of the model integrated with the other parts in order to investigate the impact of six individual and two combined conditions upon the probability of fatality. Figure 7.7 provides the results by means of a bar chart; the prior probability of fatality is also included by a black line. In all cases when the conditions are true the probability of death increases. Under individual conditions, the highest probabilities occur during heavy traffic and heavy precipitation. The combined conditions of traffic + crowds and fog + ice however produce even higher probabilities of fatality; the increase amounts in absolute terms to approximately 0.78 – 0.72 = 0.06%. To put this into context, an average of one person dies in a dwelling fire each day with the probability of death across all dwelling fires set to 0.72; if this were to rise to 0.78, it could now be expected that 0.78 / 0.72 * 1 = 1.083 people would die on each of such days, that is, when those conditions were present.

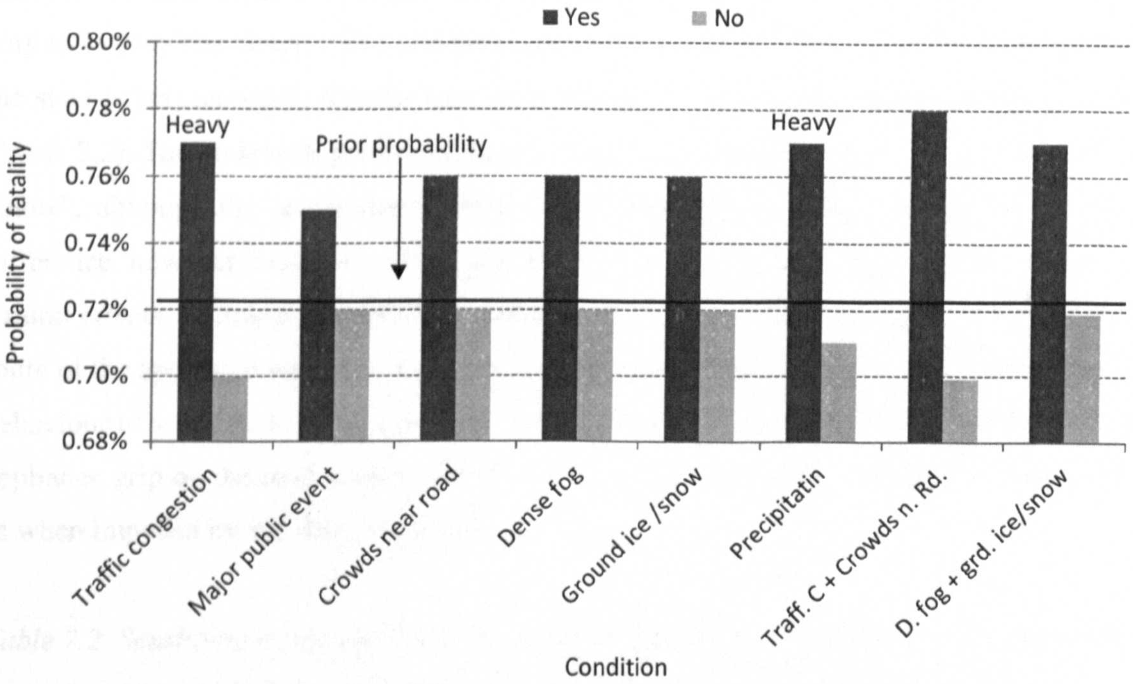


Figure 7.7. Influence of various conditions upon the probability of fatality.

The figures discussed in the previous paragraph provide a basis upon which further work could be conducted to determine whether certain procedures need to be changed on days of adverse driving conditions. For example to offset delays in travel time it may be worth considering reducing crew preparation time to a minimum. This could be achieved by avoiding kit maintenance (*e.g.* cleaning helmets, boots) or other preparatory jobs on days when these conditions are present. In terms of reducing travel time, cost-benefit analysis could be conducted to investigate if traffic light user control systems are worth investing in, to ease congestion along the route to an incident at those times.

7.5 SENSITIVITY ANALYSIS

SA was performed for part IV of the model with the hypothesis variable set to "Appliance 1 at scene" since this was one of the main outputs of this part of the model . Changes were made to two man-made environment nodes and three natural environment nodes in the same way as in previous chapter SAs and the impact on the probability of the hypothesis node to the state [<5m] recorded. Results have been tabulated ordered from most to least sensitive (Table 7.2). The node with greatest impact is "Crowds near roads" and the least "Ground ice /snow", although the sensitivity to these five nodes is fairly even. There is an apparent difference however between man-made effects to the environment when compared to natural effects. Seemingly the physical presence of obstacles (vehicles and people) along the route of the appliance will have a greater impact upon the travel time when compared to the behaviour of weather. Fog, precipitation and ice / snow will affect the driver's visibility and appliance grip on the road surface and hence travel speed would be slower, but not as slow as when impeded by vehicles and people.

Table 7.2. Sensitivity values for five input nodes acting upon the output node "response time App 1" state [<5m]. Input nodes have been ordered from most to least sensitive.

Input node:	Sensitivity value:
Crowds near roads	0.085
Traffic congestion (Heavy)	0.075
Dense fog	0.071
Precipitation (Heavy)	0.065
Ground ice / snow	0.052

7.6 FIRE TIME RESPONSE MODULE LINKED VERSIONS OF PART II AND III

The response time nodes within parts II and III of the network, presented in Chapters 5 and 6 respectively, are a function of the risk map score. Thus if the state for the node "Risk map score" was changed between [High], [Medium] or [Low] the response times would react according to the response standards set by MFRS. If analysis is desired of the factors which physically affect travel time such as weather, traffic *etc.*, then part IV of the model must come into play. For this to be possible slight modifications have to be made to parts II and III of the network. These network parts are now no longer referred to as the 'risk-map' linked versions, but rather the 'fire time response module' linked version. The nodes "Risk map score" and response time nodes have been deleted and replaced by transfer / instance nodes for response time from part IV. Figures 7.8 and 7.9 provide the modified versions of parts II and III of the network; the sections modified have been circled.

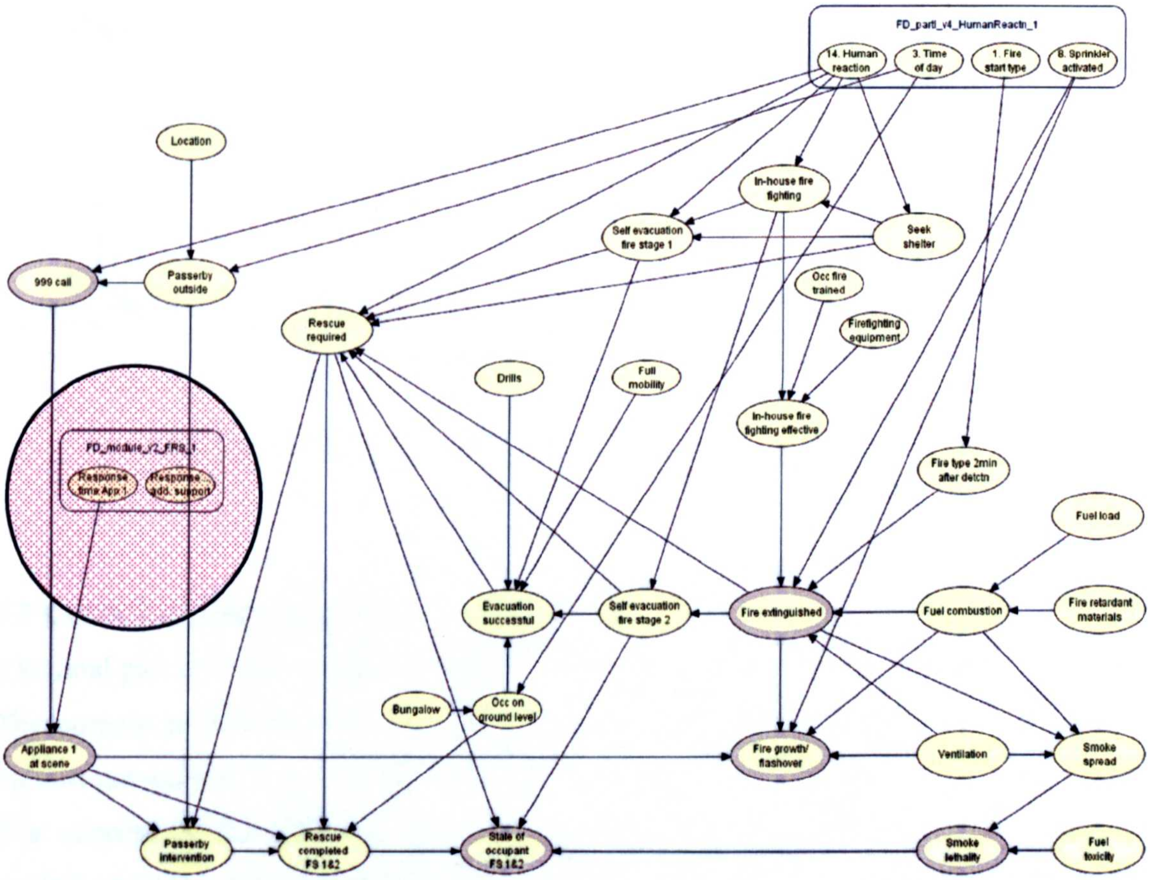


Figure 7.8. 'Fire time response module' linked version of part II.

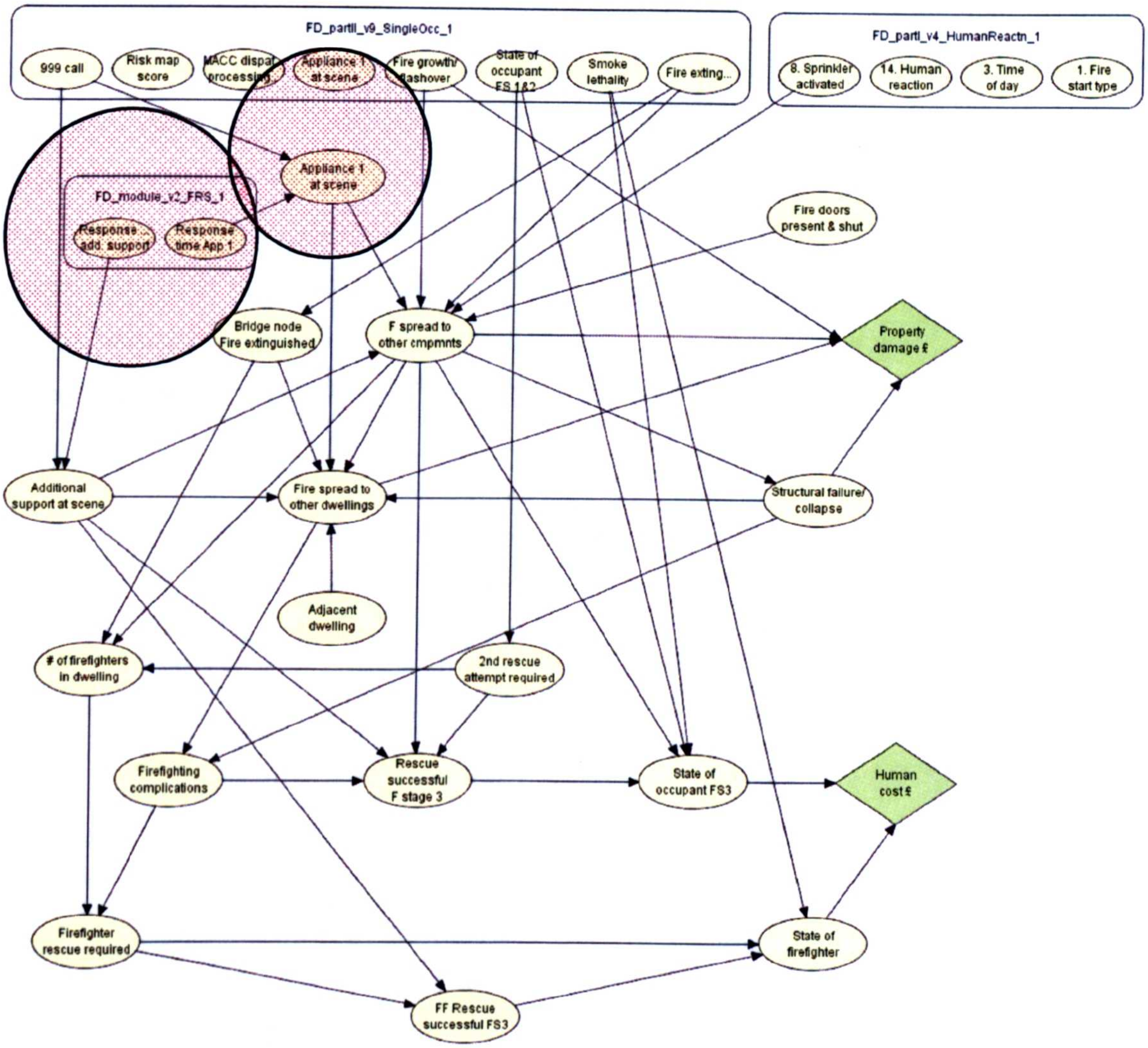


Figure 7.9. 'Fire time response module' linked version of part III.

7.7 CONCLUSIONS AND BRIEF DISCUSSION

The final part of the BN termed the *Fire time response module* is presented in this chapter. The purpose of this network is primarily to model aspects of travel time as a function of various natural and man-made environment conditions in which appliances have to operate. The concept is that FRS response times are important in reducing the risk from fire, consequently the factors that affect FRS response times must be examined to determine what role they play.

Case studies were presented to demonstrate how the model can be used. It was noted that the time of year has an effect upon travel time but that this was relatively small. Meanwhile states of weather, traffic, and crowds had a more profound effect upon travel, particularly when these conditions were combined. In terms of risk to life for combined conditions, if figures were to be extrapolated for the whole of the UK, the expected number of fatalities per day would theoretically rise from 1 to 1.083. Ideas for tackling such situations were subsequently noted with a view for potential further research.

CHAPTER 8 – DISCUSSION AND FURTHER RESEARCH

SUMMARY

This chapter discusses the research developed in this thesis focusing in particular upon the applicability of the work in a practical environment. The flexibility of the model in terms of its applicability is highlighted through the array of case studies presented earlier. The limitations of the model are identified and further research ideas proposed, some of which address these limitations.

8.1 THE RESEARCH DEVELOPED AND IT'S APPLICABILITY

This thesis develops a four-part BN for modelling dwelling fires (Chapters 4 to 7) and a risk-based fire and rescue operations management framework (Chapter 3) to facilitate rational decision making in the management of fire operations; the BN sits at the heart of the framework. The rationale for this work stems from the fact that the majority of fire fatalities occur in dwellings and that there is a lack of research in risk assessment and management of safety in this area. Although data indicates that the total number of fires in the UK is dropping year-on-year, the chance of surviving a dwelling fire has remained relatively constant since 2000 (see Chapter 2, section 2.2.4.3). The complexities of handling the interaction of the multitude of factors that affect the risk from fire mean that fire safety assessment and planning often involve high levels of uncertainty.

The four-part BN model has been built so as to be able to assess the probability of human reaction, fire growth, occupant survival, property damage, among other events of interest. The third part of the model also provides utility nodes in order to quantify the impact of fire economically. One of the purposes of this is to provide a measure of risk that FRS experts could use, however assessing how useful the model could actually be in practice would require experimentation in the field.

There are often substantial gaps between research and practice, a fact also highlighted by Hewitt-Taylor *et al.* (2012), McIntyre (2005), and Ferguson (2005). A high proportion of useful research products commonly end up simply shelved. In the present thesis, various case studies are presented which focus on "real world" issues; the idea behind this is partly to bridge the gap between the research conducted and practical concerns in the area of fire and rescue services. This is achieved by demonstrating how the model can be used and by providing a series of practical results. The case studies have been shown and discussed with fire and rescue experts who have provided positive feedback indicating that the research could potentially be used in practice. A letter of support from MFRS (Appendix 13) confirms this stating that: *"The research has certainly produced many useful outcomes with the potential to improve planning for fire and rescue service's strategies"*. The letter continues by outlining how MFRS have engaged in the project, indicating the collaboration that has taken place. Part of this collaboration involved discussions to partially validate the logic in the model. The various case studies presented have applied the model primarily as a fire risk assessment tool, but it can also be used in the capacity of a post-fire investigation tool (Chapter 4, case 4), and as a cost-benefit analysis tool for decision making (Chapter 6, case 2). It can thus be argued that there is flexibility regarding its application.

The BN model sits at the centre of the proposed risk-based fire and rescue operations management framework. For the framework to be applied, the model first needs to be proven to be useful in practice. The model interacts with several components of the framework by interchanging data; certain components are inputs to the model whilst other receivers of information. Experimentation would need to be conducted with MFRS to fine tune how this would work in practice. Another point to note is that the framework is an interpretation of the current fire and rescue operations management procedure. Even though it has been reviewed with experts, consideration must be given to the fact that FRS's are constantly evolving and that the systems and procedures that are in place presently, may change in future.

8.2 LIMITATIONS OF THE RESEARCH

The general limitations of the research have been described in Chapter 1, section 1.7. Having completed the work, the following comments can be added to the points already made in section 1.7:

- Only discrete nodes are used in the network resulting in limitations regarding modelling of continuous time-based parameters. Nevertheless, the states of these discrete nodes representing intrinsically continuous variables have been carefully defined to limit any imprecision upon the final outputs of the model.
- The number of states of some nodes has been kept to a minimum to avoid dealing with extremely large CPTs. Consequently some parameters may not be fully represented.
- Even though the model has received positive feedback from FRS experts regarding its applicability, it has not been tested in 'real' fire and rescue environments thus its practical value remains unproven.

In terms of practical applications, possibly one of the main weaknesses of the model is that it requires up to date information and statistics. The frequency in which data is updated varies between variables, thus if the model was to serve as a 'live' system, a schedule of upcoming data updates would be required and have to be implemented. Furthermore, nodes in which data was built based upon expert opinion would require reworking from time to time. However, this may not be as straight forward since the availability of experts would also change over time. New experts would replace old ones and levels of experience and epistemology would be different.

A further criticism of the model can also be made in terms of its wider application within society. The model can be used to assess risk within communities with similar socio-demographic and housing characteristics. However, establishing boundaries within towns and cities is not quite as straight forward. For example, there may be instances where an affluent row of houses are surrounded by housing estates with very different characteristics. Applying the model over the whole area under such circumstances may not be suitable.

8.3 FURTHER RESEARCH

As previously mentioned one of the advantages of BNs is that they can incorporate new parameters or even entire networks at any stage. For example if one wanted to examine how the age of an occupant affected their choice of actions and hence probability of survival during a fire, nodes to this effect could be incorporated into the network. Within Chapters 4 to 7 ideas on how each part of the network can be further developed are presented. In Chapter 4 an idea is proposed for expanding the network to study how social aspects and alcohol impact the risk from fire. This is achieved by the addition of nodes representing "Weekend", "Human sober", "Human alert", and "Deprivation index". The latter of these nodes is a government index used to measure the level of social deprivation which is linked to higher incidents of fire and casualties. Areas of low deprivation typically neglect safety and as a result such homes often do not have smoke alarms or other fire mitigating measures. Research into this aspect of fire safety could prove useful and would justify further work in the field.

Another major development for the model would be to transform it into a variable occupancy model so that the effect of a number of people could be modelled, particularly in terms of human actions / behaviour and corresponding impact upon risk. This could also permit analysis of fire safety in overcrowded homes. Chapter 6, section 6.7 presents alternate versions of parts I to III of the network designed to model variable occupancy. The variable occupancy version of part I is complete but further research is required into aspects of human behaviour in emergency situations and evacuation scenarios in order to conclude parts II and III.

Other ideas for potential further related work, some of which address the outlined research limitations, are listed below:

- Discrete decision nodes can be incorporated into the model in order to facilitate decision making based on multiple inputs such as to invest or not in sprinkler systems, to improve FRS response times, to install fire doors, and so on. An example is provided in Chapter 5, section 5.7.

- Work can be conducted into developing versions of parts I to III of the network to model apartments and other types of buildings. This would provide an improved picture of risk across a region.
- The states of FRS response times could be expanded so as to cover smaller periods of time. At present the states span 5 minutes but a more precise assessment of the impact of FRS response times could be achieved with for example 2 minute periods. The disadvantage of this however is that CPTs may become extremely large to the point where they are too difficult to manage.
- The use of continuous nodes could be explored in an alternate fashion within the modelling, though it is known that they are not compatible with utility or decision nodes within Hugin, and that they cannot be a parent of a discrete node.
- Further work can always be conducted to improve the quality of data. As has been discussed, some data sets are representative of Merseyside, others of the North West, and some of the UK. Research could be conducted on how to minimize the effect of such geographical variations.
- Research can be conducted into the application of Monte Carlo simulation to generate inputs for variables with a high degree of uncertainty or where there is no statistically significant data. This could facilitate modelling particular aspects of human behaviour and other parameters such as ventilation conditions.
- Further case studies can be undertaken and results analysed with industry experts to determine if a pilot programme can be conducted within industry. Successful field experimentation would certainly enhance the validity of the model which would pave the way for the application of the proposed risk-based fire and rescue operations management framework presented in Chapter 3.

The above suggestions are by no means exclusive. Much further research in the field of fire safety within society is required if fatalities are to be reduced to a minimum. The research produced in this thesis appears to be of use at least in theory; results from the model compare well with statistics. Ultimately though changes to operational strategy are often governed by external factors such as the wider economic picture. Nevertheless, if the work presented in this thesis can be used to support or justify specific actions to improve fire safety, then it will have proved to be of value to society.

8.4 CONCLUSIONS

A brief of review of the BN model is presented and discussion undertaken of why the research was conducted in the first place. The various ways in which the model can be used to generate results has been reviewed and its applicability in the fire service been discussed. Emphasis has been placed in particular upon the model's flexibility as a fire risk assessment tool, a post-fire investigation tool, or as a cost-benefit analysis tool. Mention was made of the risk-based fire and rescue operations management framework and how its applicability is dependent greatly upon the practical value of the BN model.

The limitations of the research have been laid out and future research ideas outlined. Some of these ideas seek to address the limitations of the current work, for example, the states of FRS response times could be increased to cover smaller time periods thus improving the representation of such variables.

CHAPTER 9 – CONCLUSIONS

SUMMARY

This chapter briefly highlights the main issues with regards to fire and safety in the UK and how FRS's direct their efforts to address this. The application of the risk-based operations management framework developed in Chapter 3 is discussed within this context. The focal point of this research project is the BN model which sits at the heart of this framework; the interaction between the model and the framework are set forth. The purpose of the BN and the process defined and applied in its construction are emphasized; finally the application and value of the model in analysing risk to life and property in dwelling fires are highlighted.

9.1 CONCLUSIONS AND RESEARCH CONTRIBUTION

This project set out to test and develop methodologies that would enable UK FRS's move towards a more rounded risk-based management regime. Research was geared towards fulfilment of the project objectives set out in Chapter 1, the conclusions of which are presented below.

Objective - Identify what the most pressing issues are in terms of fire risk reduction and investigate how risk-based operations can be utilised to address these in the UK fire and rescue sector.

This objective was dealt with in Chapter 2: Statistics indicate that the total number of fires in the UK is dropping year-on-year however most of this is due to the reduction in arson attacks. The number of accidental fires remains relatively steady. In terms of casualties, the majority of deaths (~79%) occur in dwellings. The figures indicate that the key to reducing overall risk from fires lies in dealing with dwelling fires. Due to the complexity in the way housing communities exist and how numerous factors interact to affect the risk from fire, assessing what strategies FRS's should deploy is not always clear. Much research exists on a variety of aspects of fire for example fire growth, evacuation, risk in high rise buildings, industrial fires, and so forth; however, there appears to be a lack of research addressing the risk from fires in dwellings on a vast scale, which is where this project seeks to intervene.

Objective - Develop a risk-based fire and rescue operations management framework where appropriate methods can be employed to model fire and rescue hazards as well as to make rational decisions.

Objective - Review the applicability of the conventional techniques in risk assessment of fire and rescue services.

These objectives were dealt with in Chapter 3: A risk-based fire and rescue operations management framework is proposed for MFRS in order to facilitate rational decision making with regards to investment in fire prevention measures and management of operations response based upon risk to life, property, *etc.* At the heart of the framework is the BN developed within Chapters 4 to 7 as well as MFRS's FIRS model for modelling response times as a function of available assets. The framework also incorporates hazard identification and risk estimation components which are discussed in the context of fires within residential and industrial areas.

The value of such a framework is that it captures the management of operational processes of MFRS in a manner that has not been presented before. The components link together in a rational way and interact with the BN model providing what is essentially an enhanced version of MFRS's current operational process. Specific data which feeds into the model from connected components include safety devices (*e.g.* smoke alarms, sprinkler systems), FRS response times (*e.g.* crew preparation time, appliance travel time, MACC call handling time), dwelling zone characteristics (*e.g.* location, floor levels, fire doors, detached/semi-detached/terraced), and so forth. Outputs computed from the model in terms of probabilities and utilities can then be used within linked-in components to improve decision making processes and management of operations. Such information could include for example the probability of human reaction, fire growth, fatality and injuries; it may also include the impact upon property and human wellbeing as a cost. Placing monetary value on a human life is a highly debatable and sensitive issue, nevertheless, for certain types of analysis having an idea of the human impact of a disaster in economic terms may be useful; essentially it gives a further dimension to the results.

The applicability of framework depends much upon the practical value of the BN model and how easy it would be in practice to connect with the framework components. The only way of determining this would be to conduct a field experiment involving MFRS. Nevertheless, the framework is of practical importance as it stands since it maps out the current processes of MFRS in an enhanced clear visual manner. Having such a framework can facilitate not only management of the current process, but also brainstorming new ways in which to improve the process.

Objective - Develop a flexible approach for modelling risks under uncertainties, and for risk-based decision making.

Objective - Carry out case studies to demonstrate how such modelling can be used to improve fire and rescue operations.

These objectives were dealt with in Chapters 4 to 7: Following a review of literature and risk assessment methods it was decided that the BN technique was the most suitable flexible method for modelling risk when faced with uncertainty of how parameters combine to affect risk. Furthermore a BN could also be used to quantify risk in economic terms which would facilitate cost-benefit analysis and subsequent decision making. Thus a four-part BN was built to model fires in dwellings because that is where the most pressing issues lie in terms of fire safety, as identified through the first project objective. The idea was that this network could later be tailored to model other scenarios such as apartments or office blocks; one of the advantages of BNs is that they can be expanded as required. The model in practice could be applied to assess the risk within similar groups of dwellings / neighbourhoods. The results would feed back into the proposed risk-based operations management framework in order to provide a rational basis for decision making.

The core part of the BN model was built in three parts to examine different stages of a fire, while the fourth part was designed to examine FRS response times. With *circa* one hundred nodes, building the network in this way facilitated management and arrangement of nodes. Each part of the model was constructed separately and later connected. In order to ensure consistency throughout the process of constructing each model part, an eleven step procedure was defined and applied (see Chapter 4, section 4.3.1.1). This provided an element of confidence to the actual model parts by ensuring that they were all developed to meet their specific objects, following a similar process which included brainstorming nodes, selection of nodes, reviewing with experts, collating and formulating data, testing, and so on. This eleven step procedure is in itself a contribution to knowledge since it can be applied to develop a BN model within other subject areas, particularly if this is to be a large multipart model such as the one presented in this research.

The integrated model is one the principal contributions to knowledge from this thesis, but it must also be recognised that the model parts are individual deliverables. The following points summarise what each part of the model contributes:

- Part I – the first part of the model delivers a network which replicates the initial stages of a dwelling fire. Variables which intervene in fire detection and communication of the situation to humans are represented. The output of part I is a measure of the probability of human reaction.
- Part II – the second part of the model addresses further fire development and occupant actions. Fire control measures and intervention of FRS's are modelled to deliver probabilities of fire growth and occupant survival.
- Part III – the third part of the model investigates the advanced fire situation and consequences. Further intervention of FRS appliances is accounted for and fire spread assessed. The final fire consequences are measured as both probabilities and utilities in terms of fatalities/injuries and property damage.
- Part IV – the fourth part of the model replicates the interaction of various natural and man-made factors which impact the travel time of firefighting appliances.

Various case studies have been carried out within Chapters 4 to 7 demonstrating how each part of the BN can be used either independently or as a unit. There are numerous findings discussed within each chapter relating to dynamic matters such as fire cues, human reaction, human decisions / action, impact of FRS response time, fire development, and so forth. Analysis is also undertaken of none dynamic variables such as dwelling characteristics, location, and risk-map grading. The effects of weather and traffic upon response times are examined through part IV of the model. Risk is quantified through utility nodes and the impact of many situations compared. A cost-benefit analysis is also conducted with some of the results in support of the installation of smoke alarms throughout the UK, outlining which are the most favourable options. Many of these case studies were formulated to demonstrate how the model can be applied in a practical context.

9.2 CONCLUDING STATEMENT

A brief summary of the main conclusions from the research developed in this thesis is presented below:

- A risk-based fire and rescue operations management framework has been produced which unites the principal components of the management of MFRS operations. The BN model sits at the heart of the framework and combines with various components thus delivering an enhanced operations management structure.
- An eleven step procedure for developing multipart BNs has been presented and applied.
- A four-part BN model has been produced to assess the risk from fire within similar groups of dwellings. This will allow FRS's to operate in a more efficient manner by targeting response and fire mitigation efforts where risk is highest.
- The BN model computes the probabilities of human reaction, fire growth, occupant and firefighter fatality/injury, and property damage.
- The BN model computes economic losses in terms of people and assets.
- Twelve case studies are presented from which some of the main findings were:

- Humans are far less likely to react during a smouldering fire than a flaming one; this difference is greater when there is no smoke alarm and it is night.
- Occupant actions affect significantly the probability of survival; seeking shelter within the property is particularly perilous.
- The arrival time of FRS's have a big impact upon the probability of fatality, in particular appliance 1.
- The installation of smoke alarms across England is financially justifiable based upon a cost-benefit analysis.
- Monthly weather patterns have little impact upon the travel time of fire appliances.
- The factors which impact the travel time of appliances greatest are traffic congestion followed by heavy precipitation.

The research presented in this thesis has produced a variety of contributions to knowledge, some of which are more significant than others, but all of which have the potential to be used in practice or alternatively as a base to conduct additional research. MFRS have expressed a positive interest in the work conducted which is a sign of its value. There are ongoing changes to the set-up of FRS's throughout the UK, primarily driven by policy makers who are forcing budget cuts. This may result in opportunities for research such as the one conducted in this thesis, to be considered for practical application. If FRS's are to operate with reduced capability, they must seek to improve even further the effectiveness of their operations. The research presented in this thesis may facilitate such a feat by furthering the application of risk-based techniques within fire and rescue services.

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APPENDICES

APPENDIX 1 – SUPPORTING FIRE INFORMATION FOR THE THESIS

A1.1 PRINCIPALS OF FIRES

Since several parts of this project focus on the management of fire risk and thus associated hazards, threats and consequences, it is important to have an understanding of the principals of fire. This will facilitate the analysis of fire ignition, spread, control, consequences, and extinguishment.

Fire can be defined as "*a chemical reaction or series of reactions involving the process of oxidisation, production of heat, light and smoke. There are two classes of fire: conflagration (where combustion occurs relatively slowly) and detonation (where combustion occurs instantaneously)*" (Furness 2007).

A1.1.1 Ignition

For fires to start there needs to be an interaction between three components:

- Fuel
- Heat
- Oxygen

Fire cannot occur if one of these three components is missing or is eliminated. Fundamentally fire is the result of a chemical reaction between fuel and oxygen, with heat being the catalyst. It is often represented through a triangle referred to as the "triangle of fire" (Figure A1.1).

Fire is fought on the principal of eliminating any of these components. Fuel can be removed by separating the burning material from other material so that when consumed the fire is ended. Heat can be removed or reduced by the application of water. Oxygen can be eliminated by carbon dioxide gassing or smothering the flames with sand or a fire blanket.

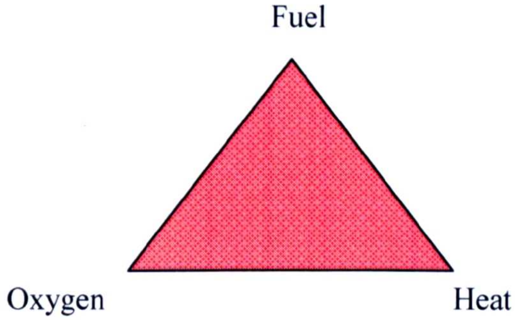


Figure A1.1. The triangle of fire

Within fire science and fire protection industries the triangle of fire has evolved into a tetrahedron with the addition of self-sustained chemical or chain reaction (Figure A1.2). The argument for including the fourth component is that there must be a chemical reaction for fire to occur. Based on this principle, and further to the fire control and extinguishment techniques outlined above, some fires are also fought by intervening in the chemical reaction via the application of chemical agents. Nevertheless, because this fourth component does not have a physical presence it is often omitted and the triangle of fire used instead to represent the science behind fire.

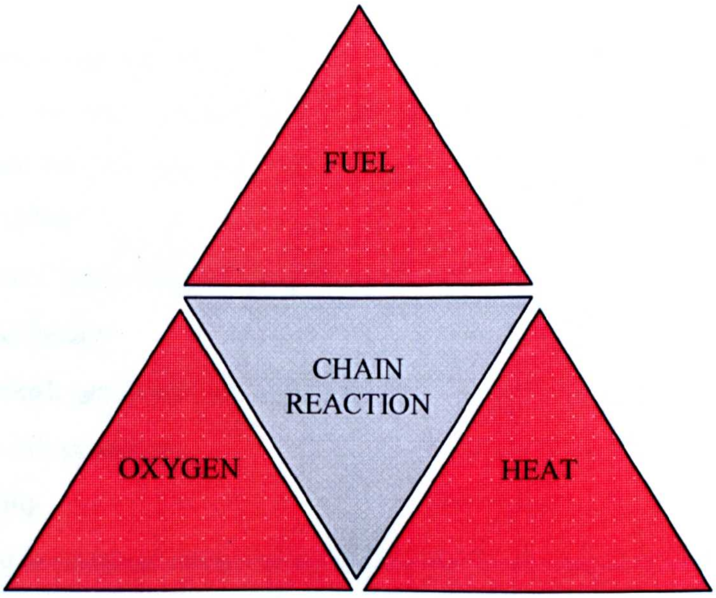


Figure A1.2. The fire tetrahedron

Fires can start anywhere as long as the components of the fire tetrahedron are present in sufficient quantities. The potential sources and characteristics of each of these components are now briefly discussed:

Fuel – Combustible matter can vary tremendously in composition, density and volatility. Sources of fuel exist in solid, liquid or gaseous states and each require different levels of heat to ignite. Common sources of fuel in man-made environments are listed below:

- Cardboard and paper
- Flammable chemicals, *e.g.* cleaning agents, petroleum derivatives, white spirit, methylated spirit, solvents
- Wood, carpets, curtains, furniture, and upholstery in general
- Ceiling tiles and polystyrene products
- Various plastics such as toys and electrical items

Certain building materials must also be considered as sources of fuel, for example, thatched roofs, hardboard, and chipboard. Consideration must also be given to finishings such as varnish, paints, and oils that may enhance flammability of sources of fuel.

Heat - In most situations oxygen, sources of fuel, and the potential for a chemical reaction already exist, but what is lacking is sufficient heat. Thus in nearly all circumstances the ignition source falls under the category of heat. This is reflected through typical causes of fire as listed below:

- Smokers' materials (cigarettes, cigars, *etc.*)
- Naked flames
- Electrical, gas or oil-fired heaters
- Hot work processes
- Cooking
- Faulty or misused electrical appliances including plugs and extension leads
- Lighting equipment especially halogen lamps

- Hot surfaces and obstructions of ventilation grills causing heat build-up
- Poorly maintained equipment that causes friction or sparks
- Static electricity
- Arson
- Natural causes (lightning, excessive heat)
- Explosions

Oxygen – This element occurs naturally in air and is essential for human existence. Unlike heat and fuel, limiting the amount of oxygen in a normal environment is not viable as a means of preventing fires. Other sources of oxygen besides air exist in the form of oxygen tanks and oxidising substances. These sources can be controlled and precautionary measures taken to reduce their potential for completing the triangle of fire.

Chemical reaction – This component, solely of the tetrahedron, is slightly different to the three components of the triangle of fire in that it is not required for ignition, but is required for fire to be maintained. The chemical reaction essentially becomes a chain reaction in which fire is sustained through its own heat by further releasing heat energy in the process of combustion. Fires can thus be extinguished by the introduction of a retardant chemical which slows or breaks down the chain reaction.

A chemical reaction is often referred to as a combustion reaction that produces heat, light, and smoke. In a controlled environment complete combustion is possible in which case the chemical reaction of, for example a methane fire, would be expressed as equation (A1.1):

$$CH_4\ (methane) + 2O_2\ (oxygen) = CO_2\ (carbon\ dioxide) + 2H_2O + heat + light \qquad \text{(A1.1)}$$

In uncontrolled environments such as building fires incomplete combustion takes place due to varying quantities of oxygen. In such cases carbon monoxide is produced and the expression becomes equation (A1.2):

$$2CH_4 + 3O_2 = 2CO\ (\text{carbon monoxide}) + 4H_2O + \text{heat} + \text{light} \tag{A1.2}$$

A1.1.2 Fire life cycle

Within a compartment the life of a fire generally begins with slow growth when the fire is small; then, as heat builds the growth rate dramatically increases. A point of stability is later reached in which the fire is maintained at a steady temperature. Finally, once fuel and/or oxygen are consumed the fire begins to slowly cool and decay. The fire life cycle (Figure A1.3) is typically divided into four stages (Furness and Muckett, 2007; Platt *et al.*, 1994; Gosseling, 1987):

- Incipient, induction, or inception phase
- Growth phase
- Fully developed or stable phase
- Decay phase

Figure A1.3. The fire life cycle.

Inception phase – This is the beginning of the fire where the components of the fire triangle come together to produce the chemical reaction. In this phase the fire is typically small, relatively cool and slowly growing.

Growth phase – This phase is where the fire starts to grow rapidly and heat release increases significantly. The rate of fire growth within enclosed environments is governed by a series of deterministic and random parameters. Deterministic parameters can be established and controlled before a fire occurs and therefore often form part of fire design or fire risk assessments. Typical deterministic parameters include:

- Fuel type
- Fuel load
- Compartment geometry and properties
- Ventilation conditions

Random parameters are difficult to pre-establish and control. They are often subject to random human behaviour depending on a series of individual circumstances. Consequently many types of fires scenarios can develop. The following are considered random parameters:

- Ignition source
- Ignition location
- Fuel arrangement / distribution
- It can also be argued that ventilation conditions (for example windows being left opened) and fuel characteristics are to an extent random, particularly in uncontrolled environments such as dwellings.

Although there are multiple fire growth scenarios fires will always fall into one of the following groups:

- Flashover fires
- Non-flashover flaming fires
- Smouldering fires

Fire growth can be analysed in a more practical way by examining these three types of fire rather than the myriad of fire growth scenarios. Because of this the model developed in this research bases fire growth and potential outcomes on the occurrence of either smouldering or flaming fires, the latter of which can later turn into a flashover fire (Chapters 4 to 6). Figure A1.4 compares the heat release rate of a flashover and non-flashover fire over time. During a flashover fire air temperatures become so high that items begin to spontaneously ignite which subsequently leads to the fire spreading extremely fast. Typical flashover air temperature is around 500 to 600°C (Quintiere, 1998; cited in Kennedy and Kennedy, 2003) meaning no human being could survive. Non-flashover fires tend to be shorter lasting and do not reach such high temperature; nevertheless, vast quantities of smoke are still given off. Smouldering fires burn at even lower temperatures but can last much longer. These fires only occur on porous materials such as fibreboard, sawdust, cardboard, certain types of cushions, *etc.* They are deceptively dangerous because they produce large amounts of smoke and toxic gases yet do not emit flames. This makes them harder to detect due to their relative low temperature; they are also silent in nature as opposed to flaming fires which 'crackle' and 'pop'. Smouldering fires can turn into flaming fires at any moment given the correct conditions.

Figure A1.4. Heat release rate curves for flashover and non-flashover fires.

Fully developed fire phase – During the fully developed fire phase the reactions are not as rapid as in the growth phase however the fire continues to burn violently consuming fuel and oxygen supplies rapidly. A fully developed fire has reached its maximum size and is characterised by large flames and masses of smoke. The fire cannot grow any further as it becomes limited by the diminishing availability of fuel and oxygen, most commonly the latter. Flashover occurs just before the fully developed fire phase is reached.

Decay phase – The final phase sees the fire temperature slowly drop until extinguished due to all fuel and/or oxygen being consumed. Flaming fires sometimes turn into smouldering fires at the very end of the process.

A1.2 CLASSIFICATION OF FIRES

Fires are classified by type to assist in recognition, documentation and investigation, fire risk assessments, and importantly the establishment of the most appropriate type of fire extinguishing medium. The British Standard EN-2 classifies fires into five groups as follows (University College of London, 2011):

Class A: Fires involving solid material where combustion normally takes place with formation of glowing embers
Class B: Fires involving liquids or liquefied solids
Class C: Fires involving gases
Class D: Fires involving metals
Class F: Fires involving cooking oils or fats

Electrical fires can fall into any of the above groups and are therefore not officially classified separately. However because they must be tackled in a specific way, they are usually included in the list under the term "ELECTRICAL". It is also worth noting that there are some differences between UK, European, and US classification of fires but these details are not really relevant to this research.

A1.3 FIRE SAFETY LEGISLATION

In their risk methodology, MFRS assume that the risk to life in commercial properties is negligible because of the stringent legislative requirements for protection systems and follow up actions to ensure compliance of these requirements. To fully understand why MFRS make this assumption, a brief review of legislative requirements is made below; in the review certain legislation is also applicable to non-commercial property such as dwellings. It is worth noting that legal requirements are categorized into *Acts of Parliament*, *Regulations*, and *Approved Documents and Guides*. The first of these being the most important while the last does not constitute the law but is merely an advisory document. The main pieces of legislation currently in place governing fire safety in the UK are as follows (Furness and Muckett, 2007; Perry, 2003; Thomson, 2002; Stollard and Abrahams, 1999):

- Fire Precautions Act 1971 - This is the current principal legislation. Its opening statement is "*An Act to make further provision for the protection of persons from fire risks; and for purposes connected therewith.*" (United Kingdom, 1971). It was brought in by the Government who were advised that a more flexible approach was necessary following the limited success of previous prescriptive legislation. It applies to various types of buildings. Several amendments have been made to the Act over recent years.
- The Fire and Rescue Services Act 2004 – The purpose of the Act is to present the structure and responsibilities of local authority Fire and Rescue Services.
- The Fire Safety and Safety of Places of Sports Act (1987) – This Act was brought in following the Bradford City Football Stadium disaster.
- The Fire Precautions (Workplace) Regulations 1997 (as amended in 1999) – This was introduced following EC Directive to harmonize health and safety standards across Europe.
- Fire Precautions (Hotels and Boarding Houses) Order 1972 – This is a certification requirement for hotels and boarding house accommodating more than six people.
- The Building Regulations for England and Wales Part B (1992) – This covers fire safety requirements and comes in under the Building Act 1984. It covers:
    - B1 - Means of escape

  - B2 – Internal fire spread (linings)
  - B3 – Internal fire spread (structure)
  - B4 - External fire spread
  - B5 - Access and facilities for the Fire Service
- Construction (Health, Safety and Welfare) Regulations 1996 – Regulations 18 to 21 deal with fire safety on construction sites.
- Furniture and Furnishings (Fire) (Safety) Regulations 1988 (amended 1989, 1993, and 2010) – These regulations set levels of fire resistance for domestic upholstered furniture, furnishings and other products containing upholstery.

Guidance relating to fire safety at work may also be sought from the Management of Health and Safety at Work Regulations (1999) and the Health and Safety at Work *etc.* Act 1974.

Further to the above a plethora of standards exist. These are published by the British Standards Institution, a sample is listed below:

- BS 476 – Fire test on building materials and structures
- BS 5041 – Fire hydrant systems equipment
- BS 5306 – Fire extinguishment installations and equipment on premises
- BS 5725 - Emergency exit devices
- BS 5588 – Code of practice for fire precautions in the design of buildings
- BS 5839 – Fire detection and alarm systems in buildings

Fire safety provisions are attached to numerous Acts related to specific building types such as children's homes, community care homes, nurseries, educational buildings, animal boarding establishments, firework factories, caravan sites, among many others. A summary list of the key legal requirements is made below in section A1.3.1.

There is a myriad of information regarding fire safety legislation and making sense of it all can be rather challenging. In this regard, useful discussion about the relevance and practicality of fire safety standards in general is made by Deakin (1999). In the paper it is suggested that "*in order to arrive at a wholly compatible package of national safety standards, which will be a help to all and a hindrance to none, a framework for future standardisation activity is needed*". In the paper Deakin also provides a review of the various pieces of legislation in place.

A1.3.1 Key legal fire legislation

Acts of Parliament:

- The Health and Safety at work etc. Act 1974 (HSW Act)
- The Environmental Protection Act 1990
- The Fire and Rescue Services Act 2004
- The Occupiers' Liability Acts 1957 and 1984
- The Employers' Liability (Compulsory Insurance) Act 1969 (and supporting regulations)
- The Disability Discrimination Act 1955
- The Water Resources Act 1991

Regulations (listed alphabetically):

- The Building Regulations 2000 (SI 20002531)
- The Chemicals (Hazardous Information and Packaging for Supply) Regulations 2002 (SI 1689)
- The Confined Spaces Regulations 1997 (SI 1713)
- The Construction (Design and Management) Regulations 2007 (SI 320)
- The Control of Major Accident Hazards Regulations 1999 (SI 734)
- The Control of Substances Hazardous to Health Regulations 2002 (SI 2677)
- The Dangerous Substances and Explosive Atmospheres Regulations 2002 (SI 2776)
- The Electricity at Work Regulations 1989 (SI 0635)
- The Gas Appliances (Safety) Regulations 1992 (SI 0711)

- The Gas Safety (Installation and Use) Regulations 1998 (SI 2451)
- The Health and Safety (Consultation with Employees) Regulations 1996 (SI 1513)
- The Health and Safety (First Aid) Regulations 1981 (SI 0917)
- The Health and Safety (Information for Employees) Regulations 1989 (SI 0682)
- The Health and Safety (Safety Signs and Safety Signals) Regulations 1996 (SI 0341)
- The Management of Health and Safety at Work Regulations 1999 (SI 3242)
- The Personal Protective Equipment Regulations 1992 (SI 2966)
- The Provision and Use of Work Equipment Regulations 1998 (2306)
- The Regulatory Reform (Fire Safety) Order 2005 (SI 1541)
- The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (SI 3163)
- The Safety Representatives and Safety Committees Regulations 1977 (SI 0500)
- The Supply of Machinery (Safety) Regulations 1992 (SI 3073)
- The Workplace (Health, Safety and Welfare) Regulations 1992 (SI 3004)

APPENDIX 2 – MFRS FIRE STATIONS AND OTHER ASSETS

A2.2 ASSETS

As of 2011 MFRS managed and operated the following assets:

- Locations:
    - 26 fire stations of which 6 are Low Level of Activity Risk (LLAR), meaning the station is manned 1000-2200 after which crew go to a nearby fire house to save on costs, where they operate on a self-roster basis. All stations have 1 or 2 appliances or pumps except for Southport which has 3 because of its geographic location and distance.
    - 1 Training and Development Academy (TDA)
    - 1 Headquarter
    - 1 MACC
    - 1 marine rescue centre
    - 1 workshop for servicing appliances
    - 1 store
- Personnel:
    - 640 full time firefighter (approximately)
    - 8 retained / part-time firefighters (approximately)
    - 1150 other staff
- Appliances:
    - 42 front line: 26 primary pumps P1 (crew of 5 + rescue equipment), 13 support pumps (crew of 4), 1 retained pump P3 (manned by retained crew), 1 hazard pump H2, 1 rescue pump (floods, rescue from rubble, *etc.*)
    - 14 reserve (these pumps can be ready within 2 hours but would only be called upon in the event of a major incident, to minimize disruption to other regions).
    - 4 stored serviceable pumps
    - 5 Combined Platform Ladder (aerial appliance)
- Supporting vehicles (types and purpose):
    - 8 prime movers
    - Specials – 1 lorry crane. This is used to transport heavy equipment and material.

  - Training school – 5 appliances. These are not equipped and used exclusively for training purposes.
  - Youth engagement – 2 appliances are used to support youth engagement programmes for problem / socially deprived children. This includes using the appliances to train youths, undertake leadership courses, *etc.*
- Other vehicles
  - 1 small fire unit. This is a blue van crewed by 3 people with the purpose of putting out small nuisance fires usually caused by youths. It is designed to be low profile in order to disappoint youths who start fires deliberately to see fire engines in action. The unit is on patrol between 1600 to 2200 when most incidents occur.
  - 1 motorbike. This is used for investigation purposes for example when automatic alarms are activated. It aims to arrive at a location before the appliances, investigate, and then radio the appliances to return to the station in cases where there has been a false alarm.
  - 1 motorbike with small pump. This is currently under development and will be used to put out small nuisance fires.
- Various demountable units carried by the prime pumps.
- Fast rescue craft within the Marine Rescue Unit

APPENDIX 3 – FIRE RISK ASSESSMENT MAP (FRAM) 2013

APPENDIX 4 – OVERVIEW OF MFRS SYSTEMS AND DATA SOURCES

Incident management

- Vision BOSS – Used by MACC for recording information from incoming calls and allocating appliances. Provides operations information.
- Vision Live – part of the Vision BOSS system but with further functions e.g. it can show high risk properties in an area. This is to be made available in future to firefighter crews on route to an incident.

Incident data

- SSR1 – completed when none fire incidents are attended
- IRS – This is completed after an incident and contains details of what happened.

Site specific risk data

- 7.2.d. – a site specific risk assessment form
- RM1 – completed when there are people within dwellings posing a high risk to firefighters (e.g. drug users, ASBOs)
- Goldmine – A database of all dwellings including details of who lives there. A company called AVCO match these records against the National Land and Property Gazetteer (NLPG).

Post incident analysis

- OWLe – This tool is used for performance management and contains details of the effectiveness of each response.

Others

- Redkite software – This is used for recording the status of equipment.
- Sophtlogic – Human resources system containing details of all personnel.
- Data Dictionary – Is essentially Metadata (data about data) whose primary function is logging all of the data types used within the databases utilized by the Merseyside Fire and Rescue Service.

APPENDIX 5 – BAYESIAN NETWORK DEFINITIONS

Some commonly quoted and easily understood definitions of BNs are provided below as support to section 4.2 of Chapter 4:

"Bayesian networks are graphical structures for representing the probabilistic relationship among a large number of variables and for doing probabilistic inference with those variables"
(Neapolitan 2004).

"A Bayesian network consists of the following:
- A set of variables and a set of directed edges between variables.
- Each variable has a finite set of mutually exclusive states.
- The variables together with the directed edges form an acyclic directed graph.
- To each variable A with parents B1, ..., Bn, a conditional probability table P(A|B1, ..., Bn) is attached.
(Jensen and Nielsen 2007)

"Directed graphs, especially DAGs, have been used to represent causal or temporal relationships (Lauritzen 1982; Wermuth and Lauritzen 1983; Kiiveri et al. 1984) and came to be known as Bayesian networks, a term coined in Pearl (1985) to emphasize three aspects: (1) the subjective nature of the input information; (2) the reliance on Bayes's conditioning as the basis for updating information; and (3) the distinction between causal and evidential modes of reasoning, a distinction that underscores Thomas Bayes's paper of 1763."
Pearl (2000)

"A BN is a probabilistic graphical model, a directed acyclic graph that represents a set of variables (nodes) and their probabilistic conditional independencies (encoded in its arcs)"
(Correa *et. at.* 2009).

"The Bayesian network model is a tool to manage uncertainty using probability. A Bayesian network is a graphical model that combines graph theory and Bayesian probability theory. Bayesian probability theory deals with the problems of reasoning under uncertainty" (Cheng and Hadjisophocleous, 2009).

A Bayesian network is a set of nodes representing random variables and a set of links connecting these nodes in an acyclic manner. Each node has assigned a function which describes how the state of the node depends on the parents of the node.
(Hugin Expert A/S 2009).

APPENDIX 6 – MARGINAL AND PRIOR PROBABILITY DISTRIBUTIONS FOR PART I OF THE BN MODEL

Marginal probability distribution for "1. Fire start type"	
State	Prob.
Flaming	0.7
Smouldering	0.3

Marginal prob. distrib. for "2. Smoke alarm installed"	
State	Prob.
Y-ionization	0.6
Y-optical	0.1
Y-combined/both	0.1
None	0.2

Marginal probability distribution for "3. Time of day"	
State	Prob.
Day 0700-2259	0.667
Night 2300-0659	0.333

Marginal prob. distribution for "4. Sprinkler installed"	
State	Prob.
Yes	0.015
No	0.985

Prior conditional probability distribution for "5. Smoke alarm sound"

Fire start type	Flaming				Smouldering			
Smoke alarm installed	Y-ionisation	Y-optical	Y-combined	None	Y-ionisation	Y-optical	Y-combined	None
Smoke alarm sound: Yes	0.8	0.75	0.8	0	0.6	0.8	0.8	0
Smoke alarm sound: No	0.2	0.25	0.2	1	0.4	0.2	0.2	1

Prior conditional probability distribution for "6. Fire or smoke visible"

Fire start type	Flaming	Smouldering
Fire or smoke visible: Yes	0.3	0.1
Fire or smoke visible: No	0.7	0.9

Prior conditional probability distribution for "7. Extensive smoke spread"

Fire start type	Flaming	Smouldering
Extensive smoke spread: Yes	0.7	0.3
Extensive smoke spread: No	0.3	0.7

Prior conditional probability distribution for "8. Sprinkler activated"

Fire start type	Flaming		Smouldering	
Sprinkler installed	Yes	No	Yes	No
Sprinkler activated: Yes	0.97	0	0.3	0
Sprinkler activated: No	0.03	1	0.7	1

Prior conditional probability distribution for "9. Human awake"

Time of day	Day 0700-2259	Night 2300-0659
Human awake: Yes	0.8	0.2
Human awake: No	0.2	0.8

Prior conditional probability distribution for "10. Human detection SOUND"

Fire start type	Flaming				Smouldering			
Smoke alarm sound	Yes		No		Yes		No	
Human awake	Yes	No	Yes	No	Yes	No	Yes	No
Human detection SOUND: Yes	0.95	0.9	0.4	0.2	0.95	0.9	0.3	0.1
Human detection SOUND: No	0.05	0.1	0.6	0.8	0.05	0.1	0.7	0.9

Prior conditional probability distribution for "11. Human detection VISUAL"

Fire or smoke visible	Yes		No	
Human awake	Yes	No	Yes	No
Human detection VISUAL: Yes	0.97	0	0	0
Human detection VISUAL: No	0.03	1	1	1

Prior conditional probability distribution for "12. Human detection SMELL"

Extensive smoke spread	Yes		No	
Human awake	Yes	No	Yes	No
Human detection SMELL: Yes	0.9	0.6	0.1	0
Human detection SMELL: No	0.1	0.4	0.9	1

Prior conditional probability distribution for "13. Human detection WET"

Sprinkler activated	Yes		No	
Human awake	Yes	No	Yes	No
Human detection WET: Yes	0.99	0.97	0	0
Human detection WET: No	0.01	0.03	1	1

Prior conditional probability distribution for "14. Human reaction"																
Human detection - SOUND	Yes								No							
Human detection - VISUAL	Yes				No				Yes				No			
Human detection - SMELL	Yes		No		Yes		No		Yes		No		Yes		No	
Human detection - WET	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Human reaction: Yes	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0
Human reaction: No	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1

APPENDIX 7 - QUESTIONNAIRE FOR MACC

Benjamin Matellini (Liverpool John Moores University)

Hello, I'm undertaking a PhD at Liverpool JMU in collaboration with MFRS. The title of the research is "A risk-based fire and rescue management system". I visited MACC early in November and found the experience very useful. I was hoping to collect some data from the MACC call team so I've put together some quick questions. Information will be fed into a model along with data gathered from other sources. The answers will be based on your experience / personal opinion and <u>will remain anonymous.</u>

Please return your questionnaire before the 15th of December 2011 either by:

QUESTIONS:

1. When an appliance is to be sent to an incident, how often will it be at a station as opposed to already being mobile (i.e. returning from another incident, training, etc.)? Please provide a percentage:
   At station %
   On road %

2. Approximately what % of calls relate to dwelling fires?

3. Considering calls relating only to dwelling fires:
   a. How long does it typically take to notify fire crews?

   b. What is shortest and longest notification time in your experience?

   c. What % of calls would be processed in:
      i. Less than 1 minute
      ii. 1 to 2 minutes
      iii. More than 2 minutes

THANK YOU FOR YOUR COLLABORATION. I realise some answers may be sensitive; please rest assured they will remain anonymous.

APPENDIX 8 – FORMULATION OF COMPLEX CPTs IN CHAPTER 5

Details on how four of the more complex CPTs from Chapter 5 were formulated are provided in this appendix.

- Node: MACC dispatch / call processing time [states: 0.75 (<1) minutes, 1.5 (1 to 2) minutes, 2.5 (>2) minutes]. Following enquiries at MACC it was established that there was no available data to construct a distribution of call time up to the point of fire crew notification for fire exclusive incidents. To get round this problem a questionnaire was put together and sent to call handlers on the Red watch in the control room at MFRS's MACC; the control room is split into four watches Red, White, Blue, and Green with each watch made up of eight operators plus two leading operators. A visit was made to MACC during the Red watch to gather information prior to the questionnaire being distributed. Only one person returned a completed questionnaire, all others declined to answer even though the survey was anonymous. The questionnaire can be found in Appendix 7. In order to gather further information personal interviews were conducted with two experts, one from MACC, the other from MFRS Headquarters. The data from the questionnaire, the personal interviews, and literature (Yung, 2008) was combined to form the CPT for this node.

  Time is continuous and therefore would be most appropriately modelled in a BN through a continuous chance node, however, as previously explained a continuous node cannot be used in the model (see Chapter 5, section 5.2.1). To get around this issue, bands of time were chosen as specified by the states of this node; essentially what should be continuous data has been discretized into three time bands. These time bands have had to be represented each by a single figure in order to integrate with other time based nodes, more specifically the time band <1 minute (m) is actually given as 0.75 m, 1 to 2 m as 1.5 m and >2 m as 2.5 m. Expert opinion highlights that it is unknown for dispatch time to have exceeded 3 m in recent years which is why the last time band (>2 m) is represented by the mid-point between 2 and 3 m, that is, 2.5 m.

- Node: Preparation + travel time appliance 1 [states: <5 minutes, 5 to 10 minutes, >10 minutes]. The data for this node was built based on the premise that the result should reflect the conditions of the response standards for the arrival of the first appliance. Thus if the dwelling was in a high risk area appliance 1 should arrive within 5 minutes, medium risk area within 6 minutes, and low risk area within 7 minutes; furthermore this should be true on 90% of occasions to mirror actual MFRS performance. Within the CPT for this node 0.9 was therefore inserted in the top left cell under the condition "high" risk for the state "<5m" of "Preparation + travel time appliance 1" (refer to Appendix 9 for a list of all CPTs). To work out the rest of the CPT an exponential decay was assumed for the remainder of the appliance probability times; this was calculated based on one minute intervals. A percentage of 70% was set as the remaining proportion of probability at the end of each subsequent time period relative to the probability at the end of the previous time period; this assumes a relatively slow to medium decay rate. Equation (A8.1) was used to work out the remaining probabilities of appliance response at time t:

$$N_{(t)} = N_{(o)} * exp^{(-t*\lambda)} \qquad \text{(A8.1)}$$

where:

$N_{(t)}$ = Quantity at time t. In this case the quantity is the probability.

$N_{(o)}$ = Initial quantity, that is quantity at time $t = 0$. In this case the initial quantity is the original remaining probability of appliance response at the end of response period set by the response standards. For "high" risk this would be after 5 minutes; t would be set to zero at this point.

t = Time from point of original remaining probability of appliance response at the end of response period

λ = Decay constant (see equation (A8.2))

$$\lambda = ln\,(1/d) \qquad \text{(A8.2)}$$

where:

d = Decay rate (0.7 in this instance)

Note that for high risk $N(_o)$ = 100% – 90% = 10%. The remaining probability after 10 minutes from fire crew notification, or 5 minutes after the first state boundary, that is $N(_{t=5})$, was subtracted from $N(_o)$ and entered into the second cell down under the column "high" risk. The remaining probability $N(_{t=5})$ was entered into the bottom cell for the state ">10m".

For "medium" risk conditions, that is, the middle column of the CPT" (see Appendix 9), the following was undertaken. Within the 90% response standard an equal distribution of response was assumed for appliance response. For the top middle cell corresponding to the state "<5m", the figure entered was 5m/6m * 90% = 75%; this again is based on the response standards which for medium risk state that appliance must arrive at the incident within 6 minutes on 90% of occasions. Note that an equal distribution within the 90% target is assumed following a discussion with experts at MFRS Headquarters of typical response times. After the 90% target an exponential decay is assumed by the author based on knowledge collected from the MFRS database. For the next cell down the exponential decay as set out in equation (A8.1) is applied on the remainder of the data. This time $N(_o)$ = 100% – 75% = 25% with *t* set to zero after 6 minutes from crew notification time. The bottom cell was completed this time with $N(_{t=4})$.

The same procedure is applied for the "low" risk column, where appliance 1 response time must be within 7 minutes on 90% of occasions, so the top cell is 5m/7m * 90% = 64.286%. The exponential decay is again applied for the remaining probability with $N(_o)$ = 100% – 64.286% = 32.284% and *t* set to zero after 7 minutes from the moment of crew notification. The bottom cell on this occasion is $N(_{t=3})$.

- Node: Response time appliance 1 [states: <5 minutes, 5 to 10 minutes, >10 minutes]. The CPT for this node (Appendix 9) was constructed essentially by aggregating the state times of its parent nodes "MACC dispatch / call processing time" and "Preparation + travel time appliance 1". To explain this, take the condition "MACC dispatch / call processing time" state [0.75 (<1m)] and "Preparation + travel time appliance 1" state [<5m]. If dispatch time is 0.75m, for "Response time appliance 1" state [<5m] to be true, "Preparation + travel time appliance 1" must be less than 5m – 0.75m = 4.25m. Assuming an equal distribution per minute the probability of this occurring must then be 4.25m / 5m = 0.85. The remaining probability 0.15 then shifts into the next time band state [5 to 10m] with zero probability in the time band state [>10m]. There is no exponential decay here since we are simply aggregating the time of the two parent nodes and calculating the probability that they fall into the corresponding states of the child node. Moving forward a column to the condition "MACC dispatch / call processing time" state [0.75 (<1m)] and "Preparation + travel time appliance 1" state [5 to 10m], a probability of zero must apply for "Response time appliance 1" state [<5m] since the latter of the parent nodes is in state [5 to 10m]. For "Response time appliance 1" state [5 to 10m] to be true, "Preparation + travel time appliance 1" must be less than 10m – 5m – 0.75m = 4.25m. The probability of this occurring must once again be 4.25m / 5m = 0.85. The remaining probability 0.15 goes into the last child node time band state [>10m]. Finally for the third column with a condition of "MACC dispatch / call processing time" state [0.75 (<1m)] and "Preparation + travel time appliance 1" state [>10m], the child node "Response time appliance 1" can only be in state [>10m] given the latter of its parent nodes being in a state [>10m]. Equations (A8.3a) and (A8.3b) provide the rule for completing "Response time appliance 1" states [<5m, 5 to 10m]; for state [>10m] the probability will always be 1 if "Preparation + travel time appliance 1" is in a state [>10m].

$$P(Chs1|Pa1sn, Pa2s1) = \frac{Parent\ 2\ state\ 1\ time\ interval - Parent\ 1\ state\ n}{Child\ state\ 1\ time\ interval} \tag{A8.3a}$$

$$P(Chs2|Pa1sn, Pa2s2) = \frac{Parent\ 2\ state\ 2\ time\ interval\ -\ Parent\ 1\ state\ n}{Child\ state\ 2\ time\ interval} \tag{A8.3b}$$

where:

Chs1 = Child node "Response time appliance 1" state 1 [<5m]

Chs2 = Child node state 2 [5 to 10m]

Pa1sn = Parent node 1 "MACC dispatch / call processing time" state [0.75m (<1m), 1.5m (1 to 2m), 2.5m (>2m)]

Pa2sn = Parent node 2 "Preparation + travel time appliance 1" state [<5m, 5 to 10m, >10m]

- Node: Appliance 1 at scene [states: <5m, 5-10m, >10m]. Data for this node was built by combining probabilities from the two parent nodes which represent times taken for a passerby or occupant to make a 999 call and for the FRS to respond; the CPT is presented below (Table A8.1) and in Appendix 9 along with all the CPTs from part II of the model. The following steps were undertaken to calculate probabilities within each cell identified through the CPT cell matrix table (Table A8.2):

Table A8.1. CPT for "Appliance 1 at scene".

Prior conditional probability distribution for "Appliance 1 at scene"									
Response time Appliance 1	<5m			5-10m			>10m		
999 call	<1m	1-3m	>3m	<1m	1-3m	>3m	<1m	1-3m	>3m
<5m	0.834	0.467	0.176	0	0	0	0	0	0
5-10m	0.166	0.533	0.752	0.834	0.467	0.176	0	0	0
>10m	0	0	0.072	0.166	0.533	0.824	1	1	1

Table A8.2. CPT cell matrix "Appliance 1 at scene".

Prior conditional probability distribution for "Appliance 1 at scene"									
Response time Appliance 1	<5m			5-10m			>10m		
999 call	<1m	1-3m	>3m	<1m	1-3m	>3m	<1m	1-3m	>3m
<5m	1x1	1x2	1x3	1x4	1x5	1x6	1x7	1x8	1x9
5-10m	2x1	2x2	2x3	2x4	2x5	2x6	2x7	2x8	2x9
>10m	3x1	3x2	3x3	3x4	3x5	3x6	3x7	3x8	3x9

COLUMN 1.

P(cell 1x1): The cell corresponds to a state [<5m] for "Appliance 1 at scene". "Response time App 1" between 0 and 4 minutes is a certainty regardless of "999 call" since this is <1m, therefore assuming an even distribution the probability of 4 out of 5 minutes would be 4m/5m = 0.8. To this the combined probability of "Response time App 1" 4 to 5 minutes and 999 call <1m has to be added. To be able to combine the data the probabilities had to be broken down to seconds assuming an even distribution. In this way each incrementing range of seconds of "Response time App 1" between 4 and 5 minutes was combined with each decreasing range of seconds of "999 call" between 0 and 1 minute, that is, <1m. The increasing / decreasing steps were applied because the aggregation of seconds could not exceed 60 seconds based on the span of "Response time App 1" between 4 and 5 minutes. Note that the probability of "Response time App 1" between 4 and 5 minutes was 1m/5m = 0.2 while the probability of "999 call" between 0 and 1 minute was 1m/1m = 1. To illustrate how the probabilities were combined two examples are given below:

For ease of writing "Response time App 1" and "999 call" shall be referred to as P(P1) and P(P2) respectively from here forwards in this section. Note that the combination of seconds cannot exceed 60 for the reasons specified above.

1st combination P(P1) seconds 0 to 1 (within the range 4 to 5 minutes) and P(P2) seconds 0 to 59;

Probability for P(P1) seconds independently would be 1 / 60 = 0.0166$^{\bullet}$

Probability for P(P2) seconds independently would be 59 / 60 = 0.9833$^{\bullet}$

But these per second probabilities must then be multiplied by the probability of the node occurring between the given minutes, that is, 0.2 for P(P1) and 1 for P(P2). Thus;

Probability for P(P1) seconds associated with node $0.0166^{\bullet} * 0.2 = 0.0033^{\bullet}$

Probability for P(P2) seconds associated with node $0.9833^{\bullet} * 1 = 0.9833^{\bullet}$

Since it is the combined probability that is being sought P(P1) must be multiplied by P(P2), thus $0.0033^{\bullet} * 0.9833^{\bullet} = 0.003278$

2nd combination P(P1) seconds 0 to 2 (within the range 4 to 5 minutes) and P(P2) seconds 0 to 58;

Probability for P(P1) seconds independently would be $2 / 60 = 0.0333^{\bullet}$

Probability for P(P2) seconds independently would be $58 / 60 = 0.9666^{\bullet}$

But these per second probabilities must then multiplied by the probability of the node occurring between the given minutes, that is, 0.2 for P(P1) and 1 for P(P2). Thus,

Probability for P(P1) seconds associated with node $0.0333^{\bullet} * 0.2 = 0.0066^{\bullet}$

Probability for P(P2) seconds associated with node $0.9666^{\bullet} * 1 = 0.9666^{\bullet}$

Since it is the combined probability that is being sought P(P1) must be multiplied by P(P2), thus $0.0066^{\bullet} * 0.9666^{\bullet} = 0.0064$

The above is repeated for all combinations of P(P1) and P(P2) range of seconds which add up to a maximum of 60, that is, 3 and 57, 4 and 56, 5 and 55, ... and ..., 59 and 1. Finally the average is taken of all the combined probabilities since an equal distribution is assumed; this gives 0.03389. This figure represents the probability of "Response time appliance 1" being between 4 and 5 minutes and "999 call" being <1m. To obtain a probability for cell 1x1 this probability needs to be added to the probability of "Response time appliance 1" being between 0 and 4 minutes and "999 call" being <1m, this was worked out earlier as 0.8. So P(cell 1x1) is 0.8 + 0.03389 = 0.834.

P(cell 2x1): P(cell 3x1) has to be zero since P(P1) state [<5m] + P(P2) state [<1m] < "Appliance 1 at scene" state [>10m]. Therefore by logic all remaining probability in column 1 must fall into cell 2x1, thus P(cell 2x1) = 1 – 0.834 = 0.166.

P(cell 3x1): This is zero since the corresponding states of P(P1) and P(P2) add up to less than 10 minutes, therefore "Appliance 1 at scene" state [>10m] cannot occur. This also applies to P(cell 3x2), P(cell 3x3).

COLUMN 2.

P(cell 1x2): The same logic used for formulating P(cell 1x1) applies here. The cell corresponds to a state [<5m] for "Appliance 1 at scene". On this occasion "Response time App 1" can occur freely only between minutes 0 and 2 since "999 call" state is [1 to 3m], thus assuming an even distribution the probability of this is 2 out of 5 minutes which is 2m/5m = 0.4. To this figure the combined probability of "Response time App 1" 2 to 5 minutes and 999 call 1 to 3m has to be added. In a similar procedure for P(cell 1x1) the probabilities are broken down into seconds assuming an even distribution. Each incrementing range of seconds of "Response time App 1" between 2 and 4 minutes was combined with each decreasing range of seconds of "999 call" between 1 and 3 minutes. The increasing / decreasing aggregation of seconds this time could not exceed 120 seconds based on the span of "Response time App 1" from 2 to 4 minutes. Minute 4 to 5 of "Response time App 1" cannot be considered otherwise the state of the child node would not be true. Note that the probability of "Response time App 1" between 2 and 4 minutes was 2m/5m = 0.4 while the probability of "999 call" between 1 and 3 minutes was 2m/2m = 1. To illustrate how the probabilities were combined one example is given below:

Note the combination of seconds in this instance cannot exceed 120 for the reasons specified above.

10th combination P(P1) seconds 0 to 10 (within the range 2 to 4 minutes) and P(P2) seconds 0 to 110;

Probability for P(P1) seconds independently would be 10 / 120 = 0.0833$^{\bullet}$

Probability for P(P2) seconds independently would be 110 / 120 = 0.9166$^{\bullet}$

These per second probabilities must then multiplied by the probability of the node occurring between the given minutes, that is, 0.4 for P(P1) and 1 for P(P2). Thus,

Probability for P(P1) seconds associated with node 0.0833$^{\bullet}$ * 0.4 = 0.0333$^{\bullet}$

Probability for P(P2) seconds associated with node $0.9166^{\bullet} * 1 = 0.9166^{\bullet}$

Since it is the combined probability that is being sought P(P1) must be *multiplied by* P(P2), thus $0.0333^{\bullet} * 0.9166^{\bullet} = 0.0306$

The above is repeated for all combinations of P(P1) and P(P2) range of seconds which add up to a maximum of 120, that is, 1 and 119, 2 and 118, 3 and 117, ... and ..., 119 and 1. The average is again taken of all the combined probabilities, equalling 0.0675. This figure represents the probability of "Response time appliance 1" being between 2 and 4 minutes and "999 call" being 1 to 3 minutes. To obtain a probability for cell 1x2 this probability needs to be added to the probability of "Response time appliance 1" being between 0 and 2 minutes and "999 call" being 1 to 3 minutes, this was worked out earlier as 0.4. So P(cell 1x2) is 0.4 + 0.0675 = 0.4675.

P(cell 2x2): Since P(cell 3x2) is zero by logic all remaining probability in column 2 must fall into cell 2x2, thus P(cell 2x2) = 1 – 0.4675 = 0.5325.

P(cell 3x2): This is zero, see P(cell 3x1) for the explanation.

COLUMN 3.

P(cell 1x3): The cell aggregates "Response time App 1" state [<5m] and "999 call" state [>3m]. The state of the latter of these parent nodes does not have an upper boundary so an alternate procedure is applied. It is known from information gathered at MFRS that the time elapsed before an emergency call tailors-off round about this point. No information was discovered on the exact decay but for simplicity an exponential distribution was applied to 999 call time in which remaining probabilities were given a half-life of one minute, that is, 50% of the probability would remain at the end of each subsequent one minute time period relative to the probability at the end of the previous time period. Equations (A8.1) and (A8.2) were applied again to work out *N(t)*, the quantity (probability remaining) at time *t*. The slightly different procedure of combining range of seconds from the two parent nodes "Response time App 1" and "999 call" is used in this instance. The maximum seconds when aggregated must still fit within the state time of the child node "Appliance 1 at scene". For cell 1x3 the child node state time is <5m, so for this maximum of 5 minutes "Response time App 1" could only be between 0 and 2 minutes due to "999 call" being >3m, thus the former was combined with "999 call" between 3 and 5 minutes. The exponential decay is applied for each time period of 1 minute but within each minute an even distribution of probabilities is assumed to facilitate the calculation. The difference with the previous procedure is that instead of combining the probability of the occurring range of seconds, the probability of each individual combination of seconds is calculated using a matrix built in Microsoft Excel. Each second of "Response time App 1" between 0 and 2 minutes was combined with each second of "999 call" between 5 and 3 minutes in which the aggregation of the two did not exceed 300 seconds based on the span of "Appliance 1 at scene" from 0 to 5 minutes. To demonstrate how the matrix was used to combine each individual combination of seconds an example is provided below. Note that the condition *P(P1) second value + P(P2) second value < 300 seconds* must be true in order for the calculation to proceed:

1st combination P(P1) second 0 (start of range 0 to 2 minutes) and P(P2) second 180 (start of range >3m).

Step 1: Check condition *P(P1) second value + P(P2) second value < 300 seconds:*

0 + 180 < 300 is TRUE so can proceed;

Step 2: Work out the proportion of the probability of "999 call" state [>3m] in the first minute (minute 3 to 4) and each subsequent minute with a decay rate *d* of 0.5. Work out the proportion per second within each time band assuming an equal distribution to facilitate the calculation; the answers are given in Table A8.3.

Step 3: Work out the probability per second independently.

Probability for P(P1) second independently would be 1 / 300 = 0.0033•. This is because P(P1) covers minutes 0 to 5 which equals 300 seconds.

Probability for P(P2) second independently is taken from Table A8.3 depending on which band it lies within. Second 180 is within band 3 to 4 minutes so probability would be = 0.008333•. Note that if another combination was being computed in which the P(P2) second being considered fell in a different minute band, for example second 245 from minute band 4 to 5, then the probability would be = 0.004167 from Table A8.3.

Since it is the combined probability that is being sought P(P1) must be multiplied by P(P2), thus 0.0033* * 0.008333* = 2.775 x 10^{-5}.

Table A8.3. Proportion of probability of "999 call" state [>3m] within each incrementing minute.

999 call > 3 minutes			
band (m)	t from 3m	proportion in time band	proportion per second in time band
n/a	0	1	
3 to 4	1	0.5	0.008333
4 to 5	2	0.25	0.004167
5 to 6	3	0.125	0.002083
6 to 7	4	0.0625	0.001042
7 to 8	5	0.03125	0.000521
8 to 9	6	0.015625	0.00026
9 to 10	7	0.007813	0.00013
10 to 11	8	0.003906	6.51E-05
11 to 12	9	0.001953	3.26E-05
12 to 13	10	0.000977	1.63E-05

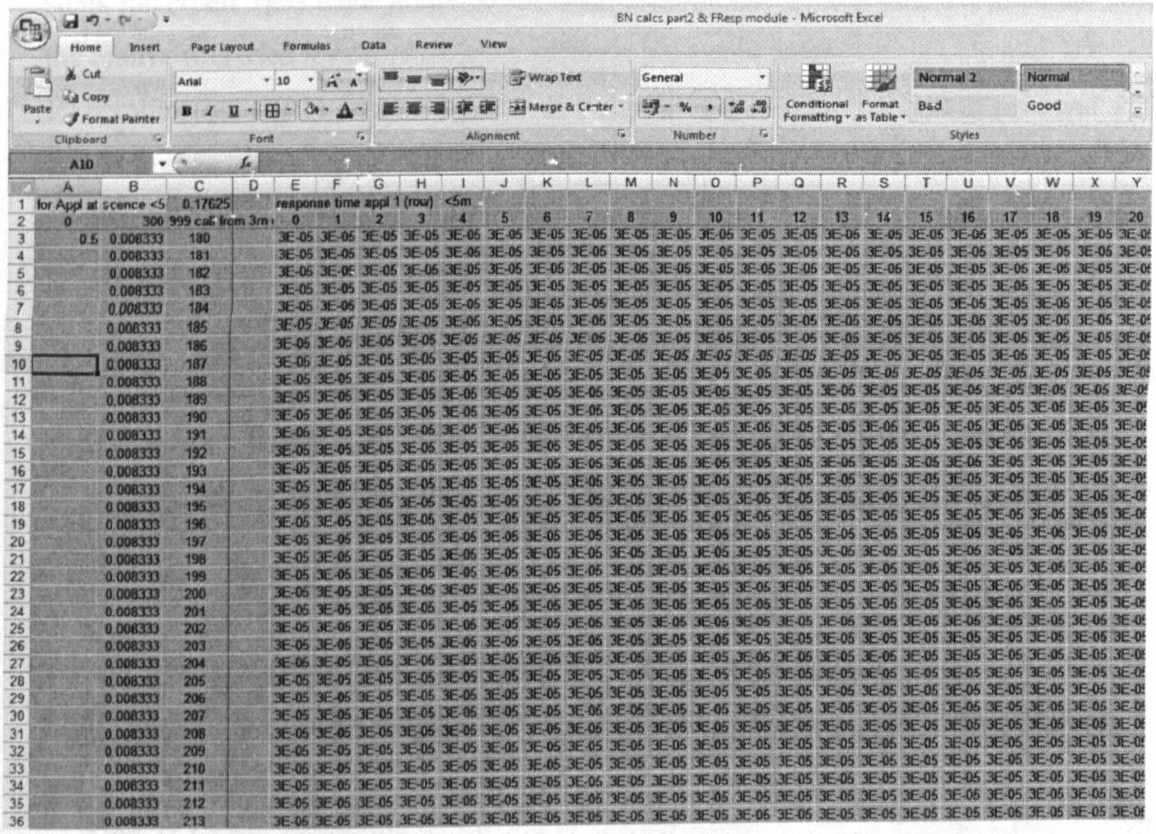
2nd combination P(P1) second 1 (start of range 0 to 2 minutes) and P(P2) second 180 (start of range >3m). The above steps are repeated. Condition *P(P1) second value + P(P2) second value < 300 seconds* is TRUE, that is, 1 + 180 < 300, so steps 2 to 3 are undertaken. This gives a probability for P(P1) second 1 and P(P2) second 180 of 2.775 x 10^{-5}.

This procedure is repeated for all combinations of *P(P1)* and *P(P2)* range of seconds which add up to a maximum of 300. This can be represented by the matrix P(P1) 0 to 119 (across) and P(P2) 180 to 299 (down) as follows below, however because there cannot be a position 0,0 all numbers are shifted forward by 1:

Let matrix S represent all combination of P(P1) + P(P2) seconds less than 300.

$$\mathbf{S} = \begin{pmatrix} s_{181,1} & s_{181,2} & \cdots & s_{181,120} \\ s_{182,1} & s_{182,2} & \cdots & s_{182,120} \\ \vdots & \vdots & \vdots & \vdots \\ s_{300,1} & s_{300,2} & \cdots & s_{300,120} \end{pmatrix}$$

All probabilities of the elements of matrix **S** were aggregated to give P(cell 1x3); this equalled 0.17625. A screenshot of the excel matrix applicable to this cell is given as an example in Figure A8.1.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	for Appl at scence <5		0.17625		response time appl 1 (row)				<5m																
2	0	300	999 cal from 3m		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	0.5	0.008333	180		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
4		0.008333	181		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
5		0.008333	182		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
6		0.008333	183		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
7		0.008333	184		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
8		0.008333	185		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
9		0.008333	186		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
10		0.008333	187		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
11		0.008333	188		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
12		0.008333	189		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
13		0.008333	190		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
14		0.008333	191		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
15		0.008333	192		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
16		0.008333	193		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
17		0.008333	194		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
18		0.008333	195		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
19		0.008333	196		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
20		0.008333	197		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
21		0.008333	198		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
22		0.008333	199		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
23		0.008333	200		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
24		0.008333	201		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
25		0.008333	202		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
26		0.008333	203		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
27		0.008333	204		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
28		0.008333	205		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
29		0.008333	206		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
30		0.008333	207		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
31		0.008333	208		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
32		0.008333	209		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
33		0.008333	210		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
34		0.008333	211		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
35		0.008333	212		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0
36		0.008333	213		3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-05	3E-0

Figure A8.1. Screenshot of the excel matrix applicable to cell 1x3.

P(cell 2x3): The same procedure described for P(cell 1x3) is applied here. The range of seconds from the two parent nodes "Response time App 1" and "999 call" is again combined. The maximum, and in this instance minimum, seconds when aggregated must fit within the state time of the child node "Appliance 1 at scene". For cell 2x3 the child node state time is 5 to 10 minutes, so to lie within this range any time for "Response time App 1" within the state [<5m] is possible given "999 call" being >3m. An exponential decay is assumed once more for the latter parent node. The minutes were broken down into seconds and the probability of each individual combination of seconds is calculated using another matrix built in Microsoft Excel. Each second of "Response time App 1" between 0 and 5 minutes was combined with each second of "999 call" between 10 and 3 minutes in which the aggregation of the two lay between 300 and 600 seconds based on the span of "Appliance 1 at scene" from 5 to 10 minutes. The same steps for P(cell 1x3) were followed for each combination of seconds. To illustrate how the matrix was used for this case an example is presented below:

1st combination P(P1) second 0 (start of range 0 to 5 minutes) and P(P2) second 180 (start of range >3m).

Step 1: Check condition *300 ≤ P(P1) second value + P(P2) second value < 600 seconds:*

$300 \leq 0 + 180 < 600$ is FALSE so CANNOT proceed.

2nd combination P(P1) second 1 (start of range 0 to 5 minutes) and P(P2) second 180 (start of range >3m).

Step 1: Check condition *300 ≤ P(P1) second value + P(P2) second value < 600 seconds:*

$300 \leq 1 + 180 < 600$ is FALSE so CANNOT proceed.

Continue with the process until the condition is met, for example,

120th combination P(P1) second 120 (start of range 0 to 5 minutes) and P(P2) second 180 (start of range >3m).

Step 1: Check condition *300 ≤ P(P1) second value + P(P2) second value < 600 seconds:*

$300 \leq 120 + 180 < 600$ is TRUE so can proceed.

Step 2: This has already been conducted for P(cell 1x3) so refer to Table A8.3.

Step 3: Work out the probability per second independently.

Probability for P(P1) second independently would be $1 / 300 = 0.0033^{\bullet}$. This is because P(P1) covers minutes 0 to 5 which equals 300 seconds.

Probability for P(P2) second independently is taken from Table A8.3 depending on which band it lies within. Second 180 is within band 3 to 4 minutes so probability would be $= 0.008333^{\bullet}$

The combined probability is thus $0.0033^{\bullet} * 0.008333^{\bullet} = 2.775 \times 10^{-5}$.

This procedure is repeated for all combinations of P(P1) and P(P2) which when added lie between 300 and 599 seconds. The matrix S in this case would be P(P1) 120 to 299 and P(P2) 180 to 599:

$$S = \begin{pmatrix} s_{181,121} & s_{181,122} & \cdots & s_{181,299} \\ s_{182,121} & s_{182,122} & \cdots & s_{182,299} \\ \vdots & \vdots & \vdots & \vdots \\ s_{600,121} & s_{600,122} & \cdots & s_{600,299} \end{pmatrix}$$

All probabilities of the elements of matrix S were aggregated to give P(cell 2x3); this equalled 0.752

P(cell 3x3): The same procedure as for cells 1x3 and 2x3 above was repeated. It is also known that P(cell 1x3) + P(cell 2x3) + P(cell 3x3) = 1 so a check of the result was carried out, that is, 1 – 0.176 – 0.752 = 0.072.

COLUMNS 4 and 5.

P(cell i x j) where i=1 to 3 and j= 4 to 5: The same procedure set out for columns 1 and 2, that is, for P(cell i x j) where in that instance i=1 to 3 and j = 1 to 2, can be applied here.

COLUMN 6.

P(cell i x 6) where i=1 to 3: The same procedure set out for column 3 was applied here since parent node "999 call" state [>3m] does not have an upper boundary.

COLUMNS 7, 8, and 9.

P(cell i x j) where i=1 to 3 and j= 7 to 9: Since parent node "Response time appliance 1" is in state [>10m] the only possibility for child node "Appliance 1 at scene" is also to be >10m.

APPENDIX 9 – MARGINAL AND PRIOR PROBABILITY DISTRIBUTIONS FOR PART II OF THE BN MODEL

PRE-CONDITIONS

1

Mariginal probability distribution for "Location"	
State	Prob.
Urban	0.7
Semi-rural	0.25
Rural	0.05

2

Mariginal PD for "Occ fire trained"	
State	Prob.
Yes	0.112
No	0.888

3

Mariginal PD for "Firefighting equipment"	
State	Prob.
Yes	0.14
No	0.86

4

Mariginal probability distribution for "Fuel load"	
State	Prob.
Yes	0.5
No	0.5

5

Mariginal PD for "Fire retardant materials"	
State	Prob.
Yes	0.7
No	0.3

6

Prior conditional probability distribution for "Fuel combustion"				
Fire retardant materials	Yes		No	
Fuel load	High	Low	High	Low
High	0.3	0.1	0.99	0.5
Low	0.7	0.9	0.01	0.5

7

Mariginal probability distribution for "Drills"	
State	Prob.
Yes	0.15
No	0.85

8

Mariginal PD for "Full mobility"	
State	Prob.
Yes	0.95
No	0.05

9

Mariginal PD for "Ventilation"	
State	Prob.
Yes	0.5
No	0.5

10

Mariginal PD for "Fuel toxicity"	
State	Prob.
Yes	0.7
No	0.3

11

Mariginal PD for "Bungalow"	
State	Prob.
Yes	0.122
No	0.878

12

Mariginal PD for "Risk map score"	
State	Prob.
High	0.0851
Medium	0.4895
Low	0.4254

HUMAN ACTIONS

13

Prior conditional probability distribution for "Occupant on ground level"				
Bungalow	Yes		No	
Time of day	Day 0700-2259	Night 2300-0659	Day 0700-2259	Night 2300-0659
Yes	0.9925	0.925	0.7	0.1
No	0.0075	0.075	0.3	0.9

14

Prior conditional probability distribution for "999 call"				
Human reaction	Yes		No	
Passerby outside	Yes	No	Yes	No
<1m	0.92	0.9	0.8	0.05
1 to 3m	0.07	0.08	0.15	0.35
>3m	0.01	0.02	0.05	0.6

15

Prior conditional probability distribution for "Seek shelter"		
Human reaction	Yes	No
Yes	0.05	0
No	0.95	1

16

Prior conditional probability distribution for "In-house firefighting"				
Human reaction	Yes		No	
Seek shelter	Yes	No	Yes	No
Yes	0	0.25	0	0
No	1	0.75	1	1

17

Prior conditional probability distribution for "Self evacuation fire stage 1"								
Human reaction	Yes				No			
Seek shelter	Yes		No		Yes		No	
In-house firefighting	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0	0	0	0.7	0	0	0	0
No	1	1	1	0.3	1	1	1	1

18

Prior conditional probability distribution for "Self evacuation fire stage 2"				
In-house firefighting	Yes		No	
Fire extinguised	Yes	No	Yes	No
Yes	0	1	0	0
No	1	0	1	1

19

Prior conditional probability distribution for "Passerby intervention"												
Rescue required	Yes						No					
Passerby outside	Yes			No			Yes			No		
Appliance 1 at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.4	0.4	0.3	0	0	0	0	0	0	0	0	0
No	0.6	0.6	0.7	1	1	1	1	1	1	1	1	1

FRS INTERACTION

20

Prior CPD for "MACC dispatch / call processing t"	
State	Prob.
0.75 (<1m)	0.99
1.5m (1-2m)	0.009
2.5m (>2m)	0.001

21

Prior CPD for "Preparation + travel time App 1"			
Risk map score	High	Medium	Low
<5m	0.9	0.75	0.6429
5-10m	0.0832	0.226	0.3228
>10m	0.0168	0.024	0.0343

22

Prior conditional probability distribution for "Response time App 1"									
MACC dispatch / call processing time	0.75 (<1m)			1.5m (1-2m)			2.5m (>2m)		
Preparation + travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	0.85	0	0	0.7	0	0	0.5	0	0
5-10m	0.15	0.85	0	0.3	0.7	0	0.5	0.5	0
>10m	0	0.15	1	0	0.3	1	0	0.5	1

23

Prior conditional probability distribution for "Appliance 1 at scene"									
Response time Appliance 1	<5m			5-10m			>10m		
999 call	<1m	1-3m	>3m	<1m	1-3m	>3m	<1m	1-3m	>3m
<5m	0.834	0.467	0.176	0	0	0	0	0	0
5-10m	0.166	0.533	0.752	0.834	0.467	0.176	0	0	0
>10m	0	0	0.072	0.166	0.533	0.824	1	1	1

OCCURRENCES / FIRE DEVELOPMENT

24 Prior conditional probability distribution for "Passerby outside"

3. Time of day	Day 0700-2259			Night 2300-0659		
Location	Urban	Suburbar	Rural	Urban	Suburbar	Rural
Yes	0.97	0.4	0.05	0.2	0.01	0.001
No	0.03	0.6	0.95	0.8	0.99	0.999

25 Prior CPD for "Fire type 2min after detctn"

Fire start type	Flam	Smou
Flamming	1	0.2
Smouldering	0	0.8

26 Prior conditional probability distribution for "In-house firefighting effective"

In-house firefighting	Yes				No			
Occupant fire trained	Yes		No		Yes		No	
Firefighting equipment	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.9	0.3	0.5	0.15	0	0	0	0
No	0.1	0.7	0.5	0.85	1	1	1	1

27 Prior conditional probability distribution for "Fire extinguished"

Ventilation	High															
Fire type 2mins after detection	Flamming								Smouldering							
Sprinkler activated	Yes				No				Yes				No			
In-house firefighting effective	Yes		No		Yes		No		Yes		No		Yes		No	
Fuel combustion	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Yes	0.9725	0.9945	0.967	0.978	0.45	0.835	0.01	0.065	0.989	0.9989	0.945	0.989	0.78	0.89	0.065	0.23
No	0.0275	0.0055	0.033	0.022	0.55	0.165	0.99	0.935	0.011	0.0011	0.055	0.011	0.22	0.11	0.935	0.77

Prior conditional probability distribution for "Fire extinguished"

Ventilation	Low															
Fire type 2mins after detection	Flamming								Smouldering							
Sprinkler activated	Yes				No				Yes				No			
In-house firefighting effective	Yes		No		Yes		No		Yes		No		Yes		No	
Fuel combustion	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Yes	0.9725	0.9945	0.967	0.978	0.45	0.835	0.01	0.065	0.989	0.9989	0.945	0.989	0.78	0.89	0.065	0.23
No	0.0275	0.0055	0.033	0.022	0.55	0.165	0.99	0.935	0.011	0.0011	0.055	0.011	0.22	0.11	0.935	0.77

28

	Prior conditional probability distribution for "Evacuation successful"																															
Self evacuatoin fire stage 1	Yes																Yes															
Self evacuatoin fire stage 2	Yes								No								Yes								No							
Occupant on ground level	Yes				No				Yes				No				Yes				No				Yes				No			
Drills	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Full mobility	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.96	0.92	0.94	0.7	0.7	0.5	0.55	0.2	0.96	0.92	0.94	0.7	0.7	0.5	0.55	0.2	0.77	0.73	0.75	0.56	0.56	0.4	0.44	0.16	0	0	0	0	0	0	0	0
No	0.04	0.08	0.06	0.3	0.3	0.5	0.45	0.8	0.04	0.08	0.06	0.3	0.3	0.5	0.45	0.8	0.23	0.27	0.25	0.44	0.44	0.6	0.56	0.84	1	1	1	1	1	1	1	1

29

	Prior conditional probability distribution for "Rescue required"																															
Human reaction	Yes																Yes															
Evacuation successful	Yes								No								Yes								No							
Self evacuation fire stage 1	Yes				No				Yes				No				Yes				No				Yes				No			
Self evacuation fire stage 2	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Seek shelter	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
No	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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	Prior conditional probability distribution for "Fire growth / flashover"																							
Ventilation	High																							
Fire extinguished	Yes												No											
Sprinkler activated	Yes						No						Yes						No					
Appliance 1 at scene	<5m		5-10m		>10m		<5m		5-10m		>10m		<5m		5-10m		>10m		<5m		5-10m		>10m	
Fuel combustion	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.001	0.09	0.07	0.1	0.08	0.6	0.4	0.9	0.85	0.95	0.9
No	1	1	1	1	1	1	1	1	1	1	1	1	0.98	0.999	0.91	0.93	0.9	0.92	0.4	0.6	0.1	0.15	0.05	0.1
	Prior conditional probability distribution for "Fire growth / flashover"																							
Ventilation	Low																							
Fire extinguished	Yes												No											
Sprinkler activated	Yes						No						Yes						No					
Appliance 1 at scene	<5m		5-10m		>10m		<5m		5-10m		>10m		<5m		5-10m		>10m		<5m		5-10m		>10m	
Fuel combustion	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.001	0.09	0.07	0.1	0.08	0.6	0.4	0.9	0.85	0.95	0.9
No	1	1	1	1	1	1	1	1	1	1	1	1	0.98	0.999	0.91	0.93	0.9	0.92	0.4	0.6	0.1	0.15	0.05	0.1

31

	Prior conditional probability distribution for "Smoke spread"							
Ventilation	High				Low			
Fire extinguised	Yes		No		Yes		No	
Fuel combustion	High	Low	High	Low	High	Low	High	Low
High	0.22	0.11	0.88	0.715	0.18	0.09	0.72	0.585
Low	0.78	0.89	0.12	0.285	0.82	0.91	0.28	0.415

32

	Prior conditional probability distribution for "Smoke lethality"			
Smoke spread	High		Low	
Fuel toxicity	High	Low	High	Low
High	0.99	0.95	0.5	0.2
Low	0.01	0.05	0.5	0.8

33

	Prior conditional probability distribution for "Rescue completed fire stage 1&2"																							
Rescue required	Yes												No											
Occupant on ground level	Yes						No						Yes						No					
Passerby intervention	Yes			No			Yes			No			Yes			No			Yes			No		
Appliance 1 at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.95	0.85	0.4	0.84	0.7	0.18	0.83	0.65	0.25	0.8	0.6	0.15	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
No	0.05	0.15	0.6	0.16	0.3	0.82	0.17	0.35	0.75	0.2	0.4	0.85	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

34

	Prior conditional probability distribution for "State of the occupant firs stage 1&2"															
Self evacuation	Yes								No							
Rescue required	Yes				No				Yes				No			
Rescue completed	Yes		No		Yes		No		Yes		No		Yes		No	
Smoke lethality	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Alive - well / minor injury	0.55	0.605	0	0	0.95	0.95	0.95	0.95	0.65	0.715	0	0	0.95	0.95	0.95	0.95
Alive - major injury	0.43	0.393	0	0	0.05	0.05	0.05	0.05	0.34	0.284	0	0	0.05	0.05	0.05	0.05
Dead	0.02	0.002	0	0	0	0	0	0	0.01	0.001	0	0	0	0	0	0
Trapped / Unknown	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0

APPENDIX 10 – MARGINAL AND PRIOR PROBABILITY DISTRIBUTIONS FOR PART III OF THE BN MODEL

PRE-CONDITIONS

1

Mariginal PD for "Fire doors present and shut"	
State	Prob.
Yes	0.25
No	0.75

2

Mariginal PD for "Adjacent dwelling"	
State	Prob.
Yes	0.8
No	0.2

FRS INTERACTION

3

Prior CPD for "Preparation + travel time Add. Support"			
Risk map score	High	Medium	Low
<5m	0.45	0.40909	0.375
5-10m	0.45	0.40909	0.375
>10m	0.1	0.18182	0.25

4

Prior conditional probability distribution for "Response time Additional support"									
MACC dispatch / call processing time	0.75 (<1m)			1.5m (1-2m)			2.5m (>2m)		
Preparation + travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	0.85	0	0	0.7	0	0	0.5	0	0
5-10m	0.15	0.85	0	0.3	0.7	0	0.5	0.5	0
>10m	0	0.15	1	0	0.3	1	0	0.5	1

5

Prior conditional probability distribution for "Additional support at scene"									
Response time Add Supp.	<5m			5-10m			>10m		
999 call	<1m	1-3m	>3m	<1m	1-3m	>3m	<1m	1-3m	>3m
<5m	0.834	0.467	0.176	0	0	0	0	0	0
5-10m	0.166	0.533	0.752	0.834	0.467	0.176	0	0	0
>10m	0	0	0.072	0.166	0.533	0.824	1	1	1

OCCURRENCES / FIRE DEVELOPMENT

6 PCPD for "Bridge node Fire extinguished"

Fire extinguished	Yes	No
Yes	1	0
No	0	1

7 Prior conditional probability distribution for "Fire spread to other compartments"

Fire extinguished	Yes																																			
Sprinkler activated	Yes																																			
Fire growth / flashover	Yes																		No																	
Fire doors present and shut	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Prior conditional probability distribution for "Fire spread to other compartments"

Fire extinguished	Yes																																			
Sprinkler activated	No																																			
Fire growth / flashover	Yes																		No																	
Fire doors present and shut	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Prior conditional probability distribution for "Fire spread to other compartments"

Fire extinguished	No																																			
Sprinkler activated	Yes																																			
Fire growth / flashover	Yes																		No																	
Fire doors present and shut	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.005	0.006	0.007	0.008	0.008	0.009	0.011	0.011	0.011	0.012	0.014	0.017	0.018	0.018	0.022	0.027	0.027	0.027	0.00005	0.00005	0.00005	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0005	0.0005	0.0005	0.001	0.001	0.001	0.002	0.002	0.002
No	0.995	0.994	0.993	0.992	0.992	0.991	0.989	0.989	0.989	0.988	0.986	0.983	0.982	0.982	0.978	0.973	0.973	0.973	0.99995	0.99995	0.99995	0.9999	0.9999	0.9999	0.9998	0.9998	0.9998	0.9995	0.9995	0.9995	0.999	0.999	0.999	0.998	0.998	0.998

Prior conditional probability distribution for "Fire spread to other compartments"

Fire extinguished	No																																			
Sprinkler activated	No																																			
Fire growth / flashover	Yes																		No																	
Fire doors present and shut	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.05	0.06	0.072	0.075	0.075	0.09	0.112	0.112	0.112	0.12	0.14	0.17	0.18	0.18	0.22	0.27	0.27	0.27	0.0005	0.0005	0.0005	0.001	0.001	0.001	0.002	0.002	0.002	0.005	0.005	0.005	0.01	0.01	0.01	0.02	0.02	0.02
No	0.95	0.94	0.928	0.925	0.925	0.91	0.888	0.888	0.888	0.88	0.86	0.83	0.82	0.82	0.78	0.73	0.73	0.73	0.9995	0.9995	0.9995	0.999	0.999	0.999	0.998	0.998	0.998	0.995	0.995	0.995	0.99	0.99	0.99	0.98	0.98	0.98

8 PCPD for "Structural failure / collapse"

Fire spread to other compartments	Yes	No
Yes	0.01	0.0001
No	0.99	0.9999

9

Prior conditional probability distribution for "Fire spread to other dwellings"																																				
Fire extinguished	Yes																																			
Adjacent dwelling	Yes																																			
Fire spread to other compartments	Yes																		No																	
Structural failure / collapse	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Prior conditional probability distribution for "Fire spread to other dwellings"																																				
Fire extinguished	Yes																																			
Adjacent dwelling	No																																			
Fire spread to other compartments	Yes																		No																	
Structural failure / collapse	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Prior conditional probability distribution for "Fire spread to other dwellings"																																				
Fire extinguished	No																																			
Adjacent dwelling	Yes																																			
Fire spread to other compartments	Yes																		No																	
Structural failure / collapse	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.1	0.15	0.2	0.2	0.2	0.25	0.4	0.4	0.4	0.05	0.075	0.1	0.125	0.125	0.15	0.175	0.175	0.175	0.05	0.075	0.1	0.125	0.125	0.15	0.175	0.175	0.175	0	0	0	0	0	0	0	0	0
No	0.9	0.85	0.8	0.8	0.8	0.75	0.6	0.6	0.6	0.95	0.925	0.9	0.875	0.875	0.85	0.825	0.825	0.825	0.95	0.925	0.9	0.875	0.875	0.85	0.825	0.825	0.825	1	1	1	1	1	1	1	1	1
Prior conditional probability distribution for "Fire spread to other dwellings"																																				
Fire extinguished	No																																			
Adjacent dwelling	No																																			
Fire spread to other compartments	Yes																		No																	
Structural failure / collapse	Yes									No									Yes									No								
Appliance 1 at scene	<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m			<5m			5-10m			>10m		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

10

Prior conditional probability distrib. for "2nd rescue attempt"				
Fire spread to other dwellings	A - well	A - mj In.	Dead	Tr / Unk
Yes	0	0	0	1
No	1	1	1	0

11

Prior conditional probability distrib. for "Firefighting complications"				
Structural failure collapse	Yes		No	
Fire spread to other dwellings	Yes	No	Yes	No
Yes	1	1	1	0
No	0	0	0	1

12

Prior conditional probability distribution for "Rescue successful fire stage 3"																								
2nd rescue attempt raquired	Yes												No											
Firefighting complications	Yes						No						Yes						No					
Fire spread to other compartments	Yes			No			Yes			No			Yes			No			Yes			No		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.8	0.75	0.7	0.8	0.75	0.7	0.96	0.93	0.9	0.99	0.975	0.96	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
No	0.2	0.25	0.3	0.2	0.25	0.3	0.04	0.07	0.1	0.01	0.025	0.04	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

13

Prior conditional probability distribution for "State of the occupant firs stage 3"																
Fire spread to other compartments	Yes															
Smoke lethality	High								Low							
State of the occupant FS 1&2	Alive - well/mi i.		Alive - major i.		Dead		Trapped		Alive - well/mi i.		Alive - major i.		Dead		Trapped	
Rescue successful FS3	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Alive - well / minor injury	1	1	0	0	0	0	0.59940	0	1	1	0	0	0	0	0.59970	0
Alive - major injury	0	0	1	1	0	0	0.39960	0	0	0	1	1	0	0	0.39980	0
Dead	0	0	0	0	1	1	0.001	1	0	0	0	0	1	1	0.0005	1
Prior conditional probability distribution for "State of the occupant firs stage 3"																
Fire spread to other compartments	No															
Smoke lethality	High								Low							
State of the occupant FS 1&2	Alive - well/mi i.		Alive - major i.		Dead		Trapped		Alive - well/mi i.		Alive - major i.		Dead		Trapped	
Rescue successful FS3	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Alive - well / minor injury	1	1	0	0	0	0	0.89910	0	1	1	0	0	0	0	0.89955	0
Alive - major injury	0	0	1	1	0	0	0.09990	0	0	0	1	1	0	0	0.09995	0
Dead	0	0	0	0	1	1	0.0001	1	0	0	0	0	1	1	0.00005	1

14

Prior conditional probability for "Number of firefighters in dwelling"								
Fire extinguished	Yes				No			
2nd rescue attemp required	Yes		No		Yes		No	
Fire spread to other compartmts	Yes	No	Yes	No	Yes	No	Yes	No
0	1	1	1	1	0	0	0	0
1	0	0	0	0	0	0.05	0	0.1
2	0	0	0	0	0.3	0.9	0.4	0.9
3	0	0	0	0	0.4	0.05	0.3	0
4	0	0	0	0	0.3	0	0.3	0

15

Prior conditional probability for "Firefighter rescue required"										
Firefighting complications	Yes					No				
Number of firefighters in dwelling	0	1	2	3	4	0	1	2	3	4
Yes	0	0.01	0.013	0.0169	0.02197	0	0.0001	0.0002	0.0003	0.0004
No	1	0.99	0.987	0.9831	0.97803	1	0.9999	0.9998	0.9997	0.9996

16

Prior conditional probability for "Firefighter rescue successful FS 3"						
Firefighter rescue required	Yes			No		
Additional support at scene	<5m	5-10m	>10m	<5m	5-10m	>10m
Yes	0.96	0.93	0.9	1	1	1
No	0.04	0.07	0.1	0	0	0

17

Prior conditional probability distrib. for "State of firefighter"								
Fire fighter rescue required	Yes				No			
Rescue successful FS 3	Yes		No		Yes		No	
Smoke spread	High	Low	High	Low	High	Low	High	Low
Alive - well/minor injury	0.49	0.6	0	0	1	1	1	1
Alive - major injury	0.49	0.398	0	0	0	0	0	0
Dead	0.02	0.02	1	1	0	0	0	0

FRS INTERACTION

18

"Property damage £" values																
Fire spread to other dwellings	Yes								No							
Structural failure	Yes				No				Yes				No			
Fire spread to other compartments	Yes		No		Yes		No		Yes		No		Yes		No	
Fire growth / flashover	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Utility	378324	378324	378324.2	378324.2	378324.2	378324.2	378324.2	378324.2	210180.1	210180	210180	210180	80838.5	80838.5	30000	7000

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"Human cost £" values									
State of the firefighter	Alive - well/minor injury			Alive - major injury			Dead		
State of the occupant	A - well	A - mj in.	Dead	A - well	A - mj in.	Dead	A - well	A - mj in.	Dead
Utility	200	155100	1.50E+06	155100	310000	1.66E+06	1.50E+06	1.66E+06	3.0E+06

APPENDIX 11 - QUESTIONNAIRE FOR FIRE CREWS

Benjamin Matellini (Liverpool John Moores University)

Hello, I'm *undertaking a PhD at* Liverpool JMU in collaboration with MFRS. The title of the research is "A risk-based fire and rescue management system". *I have visited and spoken to* various people at HQ, TDA, and MACC which I've found very useful. I am now hoping to collect some data regarding appliance travel time to incidents so I've put together some quick questions. The answers will be based on your experience / personal opinion and will remain anonymous.

Please return your questionnaire before the 15th of December 2011 either by:

Thank you for your collaboration.

QUESTIONS:

1. How long does it typically take to dispatch an appliance from a station once a call is received?

2. Imagine it took 5 minutes to arrive to an incident when roads were clear and conditions good. How many minutes / seconds would hypothetically be added to the journey due of the following factors:
    a. Heavy traffic?

    b. Crowds near pavements looking to cross roads (e.g. after a football match)?

    c. Road closure (e.g. because of marathon, road works, etc.)?

    d. Fog (less than 1 km visibility)?

    e. Heavy rain?

    f. Snow or ice on roads?

    g. Fog and snow / ice?

3. Are there any other factors that may delay journey time?

APPENDIX 12 – MARGINAL AND PRIOR PROBABILITY DISTRIBUTIONS FOR PART IV OF THE BN MODEL

CALENDAR AND DAYTIME NODES

1 Mariginal PD for "Time of year"

State	Prob.
Jan	0.0849
Feb	0.0768
Mar	0.0849
Apr	0.0822
May	0.0849
Jun	0.0822
Jul	0.0849
Aug	0.0849
Sep	0.0822
Oct	0.0849
Nov	0.0822
Dec	0.0849

WEATHER EFFECTS

2 Prior conditional probability distribution for "Air & ground frost"

Time of year	Jan		Feb		Mar		Apr		May		Jun	
Time of day	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659
Yes	0.182	0.425	0.191	0.445	0.087	0.203	0.042	0.098	0.002	0.005	0	0
No	0.818	0.575	0.809	0.555	0.913	0.797	0.958	0.902	0.998	0.995	1	1

Prior conditional probability distribution for "Air & ground frost"

Time of year	Jul		Aug		Sep		Oct		Nov		Dec	
Time of day	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659	0700-2259	2300-0659
Yes	0	0	0	0	0	0	0.015	0.036	0.098	0.229	0.147	0.343
No	1	1	1	1	1	1	0.985	0.964	0.902	0.771	0.853	0.657

3 Prior conditional probability distribution for "Ground ice / snow"

Air and ground frost	Yes			No		
Precipitation	Heavy	Light	None	Heavy	Light	None
Yes	0.95	0.95	0.1	0	0	0
No	0.05	0.05	0.9	1	1	1

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Prior conditional probability distribution for "Dense fog"												
Bridge node Time of day	Day 0700-2259											
Time of year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yes	0.0165	0.0119	0.0059	0.0042	0.0007	0.0003	0.0004	0.0011	0.0043	0.0073	0.0122	0.0192
No	0.9835	0.9881	0.9941	0.9958	0.9993	0.9997	0.9996	0.9989	0.9957	0.9927	0.9878	0.9808
Prior conditional probability distribution for "Dense fog"												
Bridge node Time of day	Night 2300-0659											
Time of year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yes	0.0248	0.0179	0.0088	0.0063	0.0010	0.0005	0.0005	0.0017	0.0064	0.0110	0.0183	0.0288
No	0.9752	0.9821	0.9912	0.9937	0.9990	0.9995	0.9995	0.9983	0.9936	0.9890	0.9817	0.9712

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Prior conditional probability distribution for "Precipitation"												
Time of year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heavy	0.032	0.030	0.031	0.026	0.041	0.062	0.043	0.060	0.048	0.068	0.068	0.051
Light	0.074	0.069	0.071	0.062	0.041	0.026	0.043	0.026	0.048	0.029	0.029	0.051
None	0.894	0.901	0.898	0.912	0.918	0.912	0.914	0.914	0.904	0.903	0.903	0.898

MAN-MADE EFFECTS

7

Mariginal PD for "Road works"	
State	Prob.
Yes	0.04
No	0.96

8

Mariginal PD for "Major public event"	
State	Prob.
Yes	0.0001
No	0.9999

9

PCPD for "Bridge node Crowd near roads"				
Bridge node Time of day	Day	Night	Day	Night
Major public event	Yes	No	Yes	No
Yes	0.2875	0.05	0.25	0.0001
No	0.7125	0.95	0.75	0.9999

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Prior conditional probability distribution for "Traffic congestion"								
Time of day	0700-2259				2300-0659			
Road works	Yes		No		Yes		No	
Major public event	Yes	No	Yes	No	Yes	No	Yes	No
Heavy	0.483	0.458	0.48	0.1	0.33	0.075	0.3	0
Light	0.483	0.458	0.48	0.8	0.33	0.075	0.3	0
None	0.034	0.085	0.04	0.1	0.34	0.850	0.4	1

SPEED AND TRAVEL TIME

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Prior conditional probability distribution for "Driving speed"												
Dense fog	Yes						No					
Ground ice / snow	Yes			No			Yes			No		
Precipitatoin	Heavy	Light	None	Heavy	Light	None	Heavy	Light	None	Heavy	Light	None
<5m	0.9	0.855	0.599	0.598	0.568	0.485	0.598	0.568	0.485	0.8	0	0
5-10m	0.1	0.145	0.4	0.399	0.429	0.485	0.399	0.429	0.485	0.2	0.9	0.001
>10m	0	0	0.001	0.003	0.003	0.03	0.003	0.003	0.03	0	0.1	0.999

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Prior conditional probability distribution for "Impact on travel time"																		
Travel congestion	Yes - heavy						Yes - slight						No					
Driving speed	re than 15% (15-45%) slo		Up to 15% slower		No effect		More than 15% slower		Up to 15% slower		No effect		More than 15% slower		Up to 15% slower		No effect	
Crowds near roads	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
-15% (<5%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.99
0% (-5% to 5%)	0	0	0	0	0	0	0	0	0.06	0.333	0.3	1	0	0	0.06	0.333	0.3	0.01
15% (5 to 25%)	0.570	0.600	0.594	0.660	0.594	0.660	0.638	0.667	0.59	0.667	0.35	0	0.638	0.667	0.59	0.667	0.35	0
30% (>25%)	0.430	0.400	0.406	0.340	0.406	0.340	0.362	0.333	0.35	0	0.35	0	0.362	0.333	0.35	0	0.35	0

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Marginal PD for "Type of appliance 1"	
State	Prob.
Appliance pump	1
Small fire unit	0
Motorbike	0

14

Marginal PD for "Type of Add Supp."	
State	Prob.
Appliance pump	1
Small fire unit	0
Motorbike	0

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Marginal PD for "Distance App 1"	
State	Prob.
Band A	0.5
Band B	0.5

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Marginal PD for "Distance AddSupp."	
State	Prob.
Band A	0.5
Band B	0.5

17

MPD for "# of major crossings loc.1"	
State	Prob.
Range 1	0.5
Range 2	0.5

18

MPD for "# of major crossings loc.2"	
State	Prob.
Range 1	0.5
Range 2	0.5

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Marginal PD for "Built-up area loc.1"	
State	Prob.
Yes	0.5
No	0.5

20

Marginal PD for "Built-up area loc.2"	
State	Prob.
Yes	0.5
No	0.5

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Prior conditional probability distribution for "Standard travel time App 1"

Type of appliance 1	Appliance pump								Small fire unit								Motorbike							
# of major road crossings loc. 1	range 1				range 2				range 1				range 2				range 1				range 2			
Built-up area loc. 1	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Distance additional support	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B
<5m	0.84375	0.84375	0.84375	0.84375	0.84375	0.84375	0.84375	0.84375	0.67500	0.67500	0.67500	0.67500	0.67500	0.67500	0.67500	0.67500	0.47250	0.47250	0.47250	0.47250	0.47250	0.47250	0.47250	0.47250
5-10m	0.15110	0.15110	0.15110	0.15110	0.15110	0.15110	0.15110	0.15110	0.28960	0.2896C	0.28960	0.28960	0.28960	0.28960	0.28960	0.28960	0.40524	0.40524	0.40524	0.40524	0.40524	0.40524	0.40524	0.40524
>10m	0.00515	0.00515	0.00515	0.00515	0.00515	0.00515	0.00515	0.00515	0.03540	0.03540	0.03540	0.03540	0.03540	0.03540	0.03540	0.03540	0.12226	0.12226	0.12226	0.12226	0.12226	0.12226	0.12226	0.12226

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Prior conditional probability distribution for "Standard travel time additional support"

Standard travel time App 1	<5m																							
Type of add. supp	Appliance pump								Small fire unit								Motorbike							
# of major road crossings loc. 2	range 1				range 2				range 1				range 2				range 1				range 2			
Built-up area loc. 2	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Distance add. support	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B
<5m	0.5550	0.5550	0.5550	0.5550	0.5550	0.5550	0.5550	0.5550	0.4440	0.4440	0.4440	0.4440	0.4440	0.4440	0.4440	0.4440	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108
5-10m	0.3577	0.3577	0.3577	0.3577	0.3577	0.3577	0.3577	0.3577	0.3972	0.3972	0.3972	0.3972	0.3972	0.3972	0.3972	0.3972	0.4112	0.4112	0.4112	0.4112	0.4112	0.4112	0.4112	0.4112
>10m	0.0873	0.0873	0.0873	0.0873	0.0873	0.0873	0.0873	0.0873	0.1588	0.1588	0.1588	0.1588	0.1588	0.1588	0.1588	0.1588	0.2780	0.2780	0.2780	0.2780	0.2780	0.2780	0.2780	0.2780

Prior conditional probability distribution for "Standard travel time additional support"

Standard travel time App 1	5-10m																							
Type of add. supp	Appliance pump								Small fire unit								Motorbike							
# of major road crossings loc. 2	range 1				range 2				range 1				range 2				range 1				range 2			
Built-up area loc. 2	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Distance add. support	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B
<5m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-10m	0.555	0.555	0.555	0.555	0.555	0.555	0.555	0.555	0.444	0.444	0.444	0.444	0.444	0.444	0.444	0.444	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108	0.3108
>10m	0.445	0.445	0.445	0.445	0.445	0.445	0.445	0.445	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.6892	0.6892	0.6892	0.6892	0.6892	0.6892	0.6892	0.6892

Prior conditional probability distribution for "Standard travel time additional support"

Standard travel time App 1	>10m																							
Type of add. supp	Appliance pump								Small fire unit								Motorbike							
# of major road crossings loc. 2	range 1				range 2				range 1				range 2				range 1				range 2			
Built-up area loc. 2	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Distance add. support	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B	band A	band B
<5m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-10m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>10m	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

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Prior conditional probability distribution for "Travel time appliance 1"												
Impact on travel time	-22.5% (<-5%)			0 (-5 to 5%)			15% (5 to 25%)			30% (>25%)		
Standard travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	1	0.3074	0	1	0	0	0.9222	0	0	0.8162	0	0
5-10m	0	0.6926	0.999	0	1	0	0.0778	0.999	0	0.1838	0.756	0
>10m	0	0	0.001	0	0	1	0	0.001	1	0	0.244	1

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Prior conditional probability distribution for "Travel time additional support"												
Impact on travel time	-22.5% (<-5%)			0 (-5 to 5%)			15% (5 to 25%)			30% (>25%)		
Standard travel time Add Supp.	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	1	0.22127	0	1	0	0	0.66381	0	0	0.58751	0	0
5-10m	0	0.77873	0.65625	0	1	0	0.33619	0.555	0	0.41249	0.405	0
>10m	0	0	0.34375	0	0	1	0	0.445	1	0	0.595	1

OTHER TIME NODES

25

MPD for "Crew preparation time"	
State	Prob.
0 (mobile)	0.1
1m (0.75-1.25)	0.4
1.5m (1.25-1.75)	0.4
2m (>1.75)	0.1

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Prior conditional probability distribution for "Preparation + travel time appliance 1"												
Crew preparation time	0 (mobile)			1m (0.75-1.25)			1.5m (1.25-1.75)			2m (>1.75)		
Travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	1	0	0	0.9	0	0	0.8	0	0	0.7	0	0
5-10m	0	1	0	0.1	0.9	0	0.2	0.8	0	0.3	0.7	0
>10m	0	0	1	0	0.1	1	0	0.2	1	0	0.3	1

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Prior conditional probability distribution for "Preparation + travel time Additional support"												
Crew preparation time	0 (mobile)			1m (0.75-1.25)			1.5m (1.25-1.75)			2m (>1.75)		
Travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	1	0	0	0.9	0	0	0.8	0	0	0.7	0	0
5-10m	0	1	0	0.1	0.9	0	0.2	0.8	0	0.3	0.7	0
>10m	0	0	1	0	0.1	1	0	0.2	1	0	0.3	1

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MPD for "MACC dispatch/call prss T"	
State	Prob.
0.75m (<1m)	0.99
1.5m (1-2m)	0.009
2.5m (>2m)	0.001

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Prior conditional probability distribution for "Response time Additional support"									
MACC dispatch / call processing time	0.75 (<1m)			1.5m (1-2m)			2.5m (>2m)		
Preparation + travel time App 1	<5m	5-10m	>10m	<5m	5-10m	>10m	<5m	5-10m	>10m
<5m	0.85	0	0	0.7	0	0	0.5	0	0
5-10m	0.15	0.85	0	0.3	0.7	0	0.5	0.5	0
>10m	0	0.15	1	0	0.3	1	0	0.5	1

APPENDIX 13 – LETTER OF SUPPORT FROM MFRS

The purpose of this statement, which you may include in your PhD thesis, is twofold: firstly I will summarize the ways in which we have collaborated with you; secondly I will outline how this research could potentially help MFRS. To this end I can state the following:

- You have engaged with various staff at MFRS from the onset of the project at all levels which I believe has helped triangulate the subjective elements uncovered during your research. This included speaking with firefighters, emergency call handlers, planning and decision makers / managers, fire investigators, risk and safety analysts, and data analysts.
- That you spent several months working with the Knowledge and Information Management team (KIM) at their offices within MFRS' headquarters in Bootle. During this time you were given access to various databases and systems in order to familiarize yourself with the activities of the service and to collate information for the project.
- That you spent many days at our Training Academy and at our library based there gathering knowledge and engaging with staff including some training experiences that have helped you rationalise some operational statements.
- That you have attended workshops, meetings and a conference in which the latest fire service issues and advancements were discussed.
- That you visited our Mobilising and Communication Centre and spoke to the team on several occasions.
- That you have sought expert opinion through meetings, emails, phone calls, and questionnaires. This information was used as inputs to your model for cases when data was not available.
- That you discussed aspects of your work with various MFRS staff at significant points of your model development in order to partially validate the outcomes.

The research you have conducted has already been beneficial to MFRS in a number of ways and there is potential for applying the model in areas of the service. The following outline some current and possible future benefits to MFRS:

- The project has raised awareness with various staff of the potential benefits research has to offer even in such a dynamic service such as fire and rescue.
- Links between MFRS and Liverpool John Moores University have been strengthened which may facilitate future joint investigation / work.

- The model has been shown to simulate a number of common situations within housing communities providing figures for probability of death, asset damage, and so forth, some of which are quantified economically. These figures could provide further evidence of why particular housing communities are labeled 'high risk'. In future, the model could be used to add an additional element to our process of mapping risk within Merseyside.
- The framework provided has clarified how the model could potentially fit-in with MFRS's operational management process and how it would interact with other tools presently used. This could potentially assist future planning of resource/appliance distribution.
- Some of the model case studies have demonstrated how it can be used as a post-fire investigation tool. This will be of interest to our post-accident investigation team.
- Confirming from an academic / numerical stance what certain staff knew through intuition and experience has been of value; some examples from the model results include what were the most appropriate actions to take during a fire, how would the arrival time of fire appliances affect the probability of escape / survival, the importance of smoke alarms expressed through probability of survival, the effect of weather and traffic on travel time of appliances, and so forth.
- The model could also be useful for assessing the combined effect of several variables upon the probability of survival. Currently there is no tool for undertaking such an evaluation.

I hope that this statement will add due value to your PhD thesis which I think is rightly a body of work that can potentially add some real value to strategic policy.

Yours sincerely,

Rob Pritchard
(Sefton District Manager)