EXPERT ELICITATION OF UNCERTAINTY IN PSYCHOLOGICAL RESPONSE IN A FIRE EVACUATION USING BAYESIAN NETWORK

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by

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LIST OF SYMBOLS

a_{ij}	TFN parameter for *j*-th linguistic term
a_{x_c}	Assignment of states of parent node
$a_{neg,k+}$	Assignment of $pa(X_c)$ in which X_k in its most favorable state and other X_k are in their least favourable state for low ordered state of X_c
a_{neg}	Assignment of the best combination of states of parent nodes for low ordered state of X_c
a_{pos}	Assignment of the best combination of states of parent nodes for high ordered state of X_c
E_u	Expert u
f_{x_c}	Linear function
I_{ind}	Individual influence factor
I_{joint}	Joint influence factor
$I_{max,k}$	Interval of maximum $(I_{ind}(x_k), I_{joint}(a))$
$I_{min,k}$	Interval of minimum $(I_{ind}(x_k), I_{joint}(a))$
k_l	Score for k classification and l constitution of different expert
m_u	Relative importance of expert *u*
$S^-(X_k, X_c)$	Parent nodes with negative influences on X_c
$S^+(X_k, X_c)$	Parent nodes with positive influences on X_c
S_{uv}	Degree of agreement between expert *u* and expert *v*
SV	Sensitivity value
w_k	Weight for parent node X_k
WS_u	Weighting score of expert *u*
w_u	Weight of expert *u*
X_c	Discrete random variable of child node

$x_{c,max}$	Maximum value of X_c
$x_{c,min}$	Minimum value of X_c
X_k	Discrete random variable of parent node
$x_{k,max}$	Maximum value of X_k
$\mu_{\tilde{A}}(x)$	Membership function of $\tilde{A}$
β	Relaxation factors
(a_1, a_2, a_3)	TFN parameter
$(\tilde{A}, \tilde{R})$	Z-number

LIST OF ABBREVIATIONS

AA	Average Agreement Degree
ABM	Agent Based Model
AC	Audio Fire Cues
AWAD	Average Weight Agreement Degree
BN	Bayesian Network
CAM	Consistency Aggregation Method
CDC	Consensus Degree Coefficient
CER	Certain
CPT	Conditional Probability Table
E	Escape
EBBN	Elicitation for Bayesian Belief Network
EPRiF	Elicitation of Psychological Response in a Fire
ES	Emotional Stability
ETA	Event Tree Analysis
EXP	Expected
FC	Fire Cues
FCH	Fair-chance
FK	Fire Knowledge
FRDM	Fire and Rescue Department of Malaysia
FTA	Fault Tree Analysis
H	High
HREC	Human Research Ethics Committee
IE	Interval Estimation
IPR	Improbable
IPS	Impossible
L	Low
LF	Layout Familiarity
M	Medium
MFE	Membership Function Exemplification
MFs	Membership Functions
N/A	Not Available Information

P	Polling
PC	Pair-wise Comparison
PE	Point Estimation
PH	Perceived Hazard
PI	Psychological Incapacitation
PRiF	Psychological Response in a Fire
PRO	Probable
RAD	Relative Agreement Degree
RR	Reverse Rating
RWAD	Relative Weight Agreement Degree
SAM	Similarity Aggregation Method
ST	Stress
TFN	Triangular Fuzzy Number
TIE	Transition Interval Estimation
TP	Time Pressure
UNC	Uncertain
VC	Visual Fire Cues
VH	Very High
VL	Very Low
VR	Virtual Reality

LIST OF APPENDICES

ELISITASI PAKAR MENGENAI KETIDAKPASTIAN RESPONS PSIKOLOGI DALAM EVAKUASI KEBAKARAN MENGGUNAKAN RANGKAIAN BAYESAN

ABSTRAK

Pada peringkat awal kebakaran di dalam bangunan, respons psikologi manusia menjadi ciri penting dalam menentukan kemandirian hidup. Model Rangkaian Bayesan (BN) telah menjadi salah satu pilihan dalam kalangan para penyelidik dalam mewakili pengetahuan yang tidak pasti tentang respons psikologi dalam sistem evakuasi. Kebanyakan model respons psikologi BN mempunyai latar belakang literatur tingkah laku manusia dalam kebakaran bangunan. Walau bagaimanapun, struktur dan kuantifikasi model hampir mengabaikan pendapat daripada pakar pengetahuan domain. Oleh itu, objektif kajian ini adalah untuk menangani ketidakpastian dalam model BN respons psikologi semasa evakuasi kebakaran melalui elisitasi pakar. Model konseptual baru iaitu PRiF (Respons Psikologi dalam Kebakaran) dibangunkan melalui teori saintifik sains dan teori bencana dan kebakaran serta pendekatan pendapat pakar. Bagi tujuan model kuantifikasi, dua fasa pengumpulan data yang melibatkan tujuh pakar dari aliran akademik dan pengamal profesional kebakaran dijalankan. Pada fasa pertama, skala penukaran baru sebagai alat bantuan elisitati, Skala Kebarangkalian Kabur dibangunkan dengan meminta pakar untuk mendapatkan fungsi keahlian bagi istilah linguistik dalam skala. Fasa kedua memerlukan pakar untuk mengkuantifikasi model PRiF menggunakan konsep Z-number, yang mana dapat menangani ketidakpastian dan mengambil kira kebolehpercayaan anggaran mereka. Pakar membuat inferens melalui skala penukaran yang dibangunkan dan memberikan keyakinan terhadap pertimbangan mereka. Untuk menggabungkan pendapat pakar, Kaedah Agregat Keserupaan (SAM) berpemberat pakar dicadangkan dengan memasukkan faktor berpemberat pakar berdasarkan latar belakang kepakaran mereka. Penemuan daripada proses elisitati pakar menunjukkan bahawa kegagalan evakuasi kebakaran dipengaruhi oleh faktor psikologi *Tekanan Masa*. Ujian pengesahan menunjukkan bahawa struktur model PRiF adalah sejajar dengan literatur tingkah laku manusia dalam evakuasi kebakaran dan parameter yang ditaksir dalam model ini adalah sesuai. Pendekatan elisitati baru dalam kajian ini mempunyai kelebihan dalam menangani ketidakpastian model kerana mengambilkira kebolehpercayaan anggaran pakar, memudahkan pakar dalam membuat inferens dan mempunyai asas pengetahuan spesifik domain tentang respons psikologi dalam evakuasi kebakaran.

EXPERT ELICITATION OF UNCERTAINTY IN PSYCHOLOGICAL RESPONSE IN A FIRE EVACUATION USING BAYESIAN NETWORK

ABSTRACT

In the early stage of a fire in a building, the human psychological response becomes an important feature in determining survival. Bayesian Network (BN) model has been one of the preferred choices among researchers in representing uncertain knowledge about the psychological responses in the evacuation system. The BN psychological response models mostly have a literature background of human behaviour in a building on fire. However, the model structure and quantification are almost not involving the opinion of experts in the domain knowledge. Therefore, the goal of this study is to address the uncertainties in the BN model of psychological response during a fire evacuation through expert elicitation. A new conceptual model namely the PRiF (Psychological Response in a Fire) is developed through the social scientific theory and the disaster and fire theory as well as expert opinion approach. For the purpose of model quantification, two phases of data collections involving seven experts from the academic stream and professional fire practitioners are conducted. In the first phase, a new conversion scale for an aided elicitation tool, the Fuzzy Probability Scale is constructed by the experts to elicit the membership functions of the linguistic terms in the scale. The second phase requires the experts to quantify the PRiF model using the Z-number concept, which is able to address the expert's uncertainty and includes the reliability of their estimates. In doing this, the experts infer their beliefs using the developed conversion scale and provide the confidence of their judgments. To aggregate the expert's opinions, an expert weighted Similarity Aggregation Method (SAM) that includes the expert's weighting factor based on their expertise background is proposed. Finding from the expert elicitation process suggests that an unsuccessful safe fire evacuation is highly influenced by the psychological factor *Time Pressure*. The validation studies show that the PRiF model is in line with the literature of human behaviour in the fire evacuation and the assessed parameters in the model are reasonable. The new elicitation approach in this study has an advantage in addressing the model's uncertainty as it includes the expert's reliability of the estimates, is convenient for the experts to infer their beliefs and has a domain-specific knowledge base of psychological response in a fire evacuation.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter begins with the motivation of the research and a glimpse of the human behaviour during building fires, followed by details of the research background of the fire evacuation modelling. The research problems, research objectives, research scope, research process and research contributions are presented subsequently. Finally, this chapter briefly summarises the organisation of this thesis.

1.2 Research motivation

A life-threatening situation such as the event of a fire can be a triggered event, which could lead to damage of belongings and property, injuries or casualties of human lives. Even though fires are rare occurrences, however, when they do happen the impact is extreme, or so-called ‘low probability - high consequences’ incidents. In the early stage of a fire in a building, the safe escape process is the most crucial aspect of fire events. Nevertheless, a safe escape from a building on fire is not always possible, which can lead to potential injuries and deaths due to actions or reactions that people take in responding to the fire. Generally, a fire takes place without warning in which building occupants have limited time to react that may result in deaths and injuries.

According to the fire annual statistics from the federal fire and rescue services agency in Malaysia, the Fire and Rescue Department of Malaysia (FRDM), from the year 2011-2018, there is a total of 303,649 fire cases, with an average of 37,956 cases annually (Fire and Rescue Department of Malaysia, 2019). Of the fire cases, 14.3%

(43,416) are building fires, with an average of 5427 cases annually. An average value of more than 2000 cases annually is considered high in Malaysia (Yatim, 2009). In 2017, building fires has a larger proportion of fire cases (21.1%) as compared to other fire type such as orchard and bushes (20.4%), vehicles (12.7%), rubbish (12.7%), machines and utensils (5.7%), forest (3.1%), gas, chemical and petrol (2.1%), and stall (0.4%). Having a high proportion of fire cases means that the occupants in the buildings are at the highest risk in getting injuries or resulting in death.

From the year 2011-2018, death and injuries due to fire outbreaks generally have an upward trend (see Figure 1.1). Compared to less than 100 cases in 2013, the number of death cases increased to more than 100 cases for the following four years (except for the year 2018), with the highest reported cases in 2017. There was a sharp increase in injuries in 2014 (389 cases), however, the number of cases remains the lowest for the following five years.

In 2016, the proportion of death is 0.21% and injuries 0.96% from a total of 49,875 fire cases reported while in 2017 the proportion of death is 0.56% and injuries 1.52% from a total of 29,356 fire cases reported. Even though the number of total fire cases largely decreased (-41.1%) from 2016 to 2017, the fraction of people that died and are injured relatively increased in 2017 as compared to the previous year of 2016. Meanwhile in 2018, the proportion of death is 0.26% and injuries 1.08% from a total of 36,758 fire cases reported, a slight decrease as compared to the year. However, the number of total fire cases has increased by 25.2%. In many cases, the death and injuries occur at the place of occurrence due to failure to escape (Bakar, 2016).

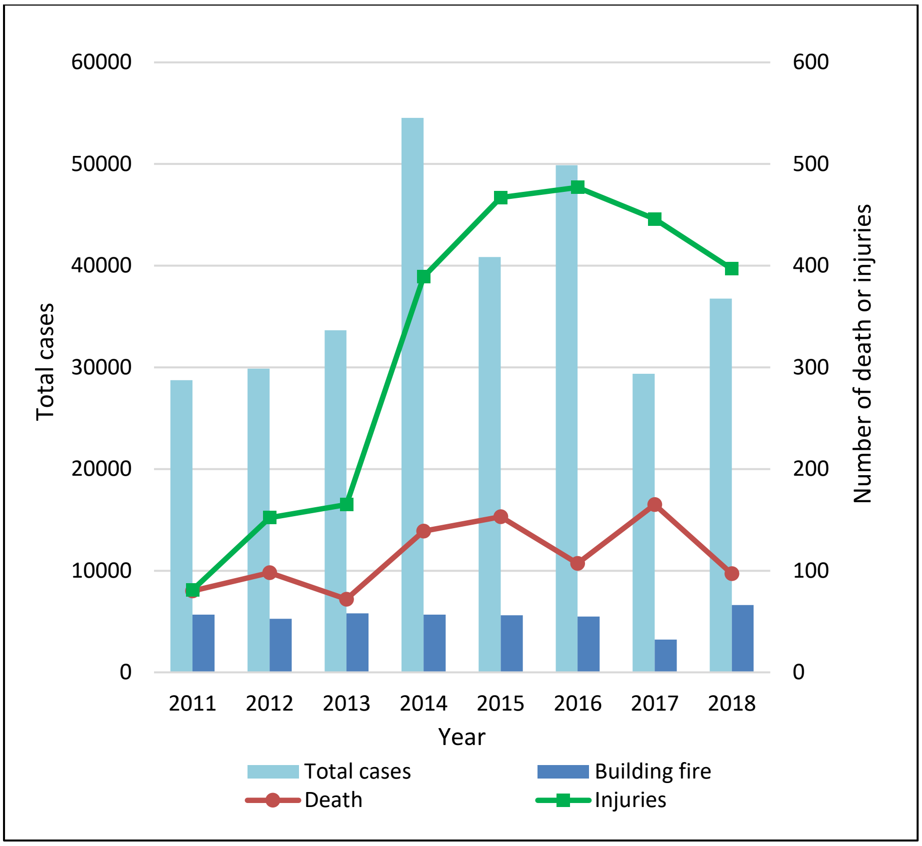

Figure 1.1 Statistics of fire breakouts in Malaysia, 2011 – 2018
Source: Fire and Rescue Department of Malaysia (FRDM)

Notwithstanding a building having met all safety regulations, codes and standards, the success of reducing the fire risk and achieving a safe evacuation depends on the human behaviour which relates to how people behave in a fire (Kobes, Helsloot, de Vries, & Post, 2010a). Research on the human behaviour during building fires has received a considerable amount of attention from the multi-disciplinary perspectives such as fire protection engineering, evacuation modelling, psychology, computer science, applied mathematics and many more (Kinateder & Ronchi, 2019; Kobes et al., 2010a). Recently, there has been an increasing interest in defining behavioural actions of occupants in fire situations from the psychological or cognitive perspective such as how individual threat perceptions and decision-making under emergency situations (Aguirre, 2005; Kinateder & Ronchi, 2019; Kobes et al., 2010a).

However, the study concerning the human behaviour during building fires from the perspective of psychology in Malaysia is very new and very limited resources are available to review (Subramaniam, 2004; Tharmarajan, 2007; Yatim, 2009). This study aims to contribute to this growing area of research by exploring a better understanding of the psychological perspective of human behaviour to reasonably predict the response and actions taken, subsequently reducing the risk of death or injury during crises.

1.3 Human behavior during building fires

The threat of fire is always present in buildings and can be particularly dangerous to building occupants. A building is a physically enclosed environment in which people carried out their activities by the building use. According to Ronchi and Nilsson (2013), the main building uses can be categorised into office buildings, residential buildings and health care facilities. Each of these categories presents different characteristics from the point of view of both the infrastructure and the population. In a building fire, the fire incident generally starts at a single location within a room, or compartment but if not adequately controlled, the adjacent rooms and indeed the whole building will be at risk (Yatim, 2009).

The term fire evacuation refers to the process of a safe escape from the threat of fire to a safer place outside of the building. Whereas the term evacuee refers to the people or building occupant in the process of the evacuation. Literature highlights three factors that are involved in the evacuation of occupants during building fires (Kobes et al., 2010a; Proulx, 2001). They are fire characteristics, building characteristics, and human characteristics:

a) fire characteristics

The first factor, fire characteristics which revolve around the nature of the fire itself have a direct influence on fire events. A fire can usually take place only when three things are present: oxygen, material and heat as featured in the classic "fire triangle" (Belcher, Collinson, & Scott, 2013). The fire characteristics resulted from the process of a fire such as the smoke yield, fire growth rate, toxicity, and heat generated are among the reliable indicators of a fire and the need to escape (Proulx, 2003).

b) building characteristics

The second factor is the building characteristics where the fire took place. A building must be designed by specification and rules to provide a satisfactory escape route. In Malaysia, the specifications for the design and construction of escape routes in buildings currently are based on the building regulations, i.e., the Uniform Building By-Laws 1984. Fire safety in a building can be achieved through building design features intended to minimise the risk of people from a fire (Yatim, 2009). The physical characteristics such as the layout, materials, size of building and exit routes constitute the environment in which people can survive in a fire (Kobes et al., 2010a).

c) human characteristics

Finally, the third factor is the characteristics of building occupants that determine the ability and willingness to act effectively (Proulx, 2001). Occupants play a vital role in lowering the risk of a fire if they are well-behaved and act appropriately during an evacuation. How people behave or take actions in response to a fire is referred to as the human behaviour (Pires, 2005).

To date, many efforts have been done in lowering the fire risk that are focused either on the fire characteristics – including fire dynamics, combustion and toxicity assessment (Cha, Han, Lee, & Choi, 2012; Purser, 2002), or building characteristics – including building fire safety system, design and construction, and fire safety engineering (Lee, Cheon, Hyun, & Park, 2013; Liu, Zhang, & Zhu, 2012; Sassi et al., 2016). However, there is lack of research in understanding the human behavior, as human characteristics are difficult to be quantified or modelled in a fire evacuation system (Cheng et al., 2019, Lin, Zhu, Li, & Becerik-Gerber, 2020). Behavioural analysis is generally used in the psychology study, but lately, its application has been extended to a broader area of social concern, including the fire evacuation study.

In the event of a fire, Kobes et al. (2010a) defined the human behaviour as “the action people take based on a situation, and the considerations involved before these actions are carried out”. There are a number of human factors that could simultaneously have an impact on an occupant’s behaviour during a fire, as discussed in Proulx (2001) and Kobes et al. (2010a). In this study, we categorised the human behaviour into the physical, psychological and social characteristics as follows (see Figure 1.2):

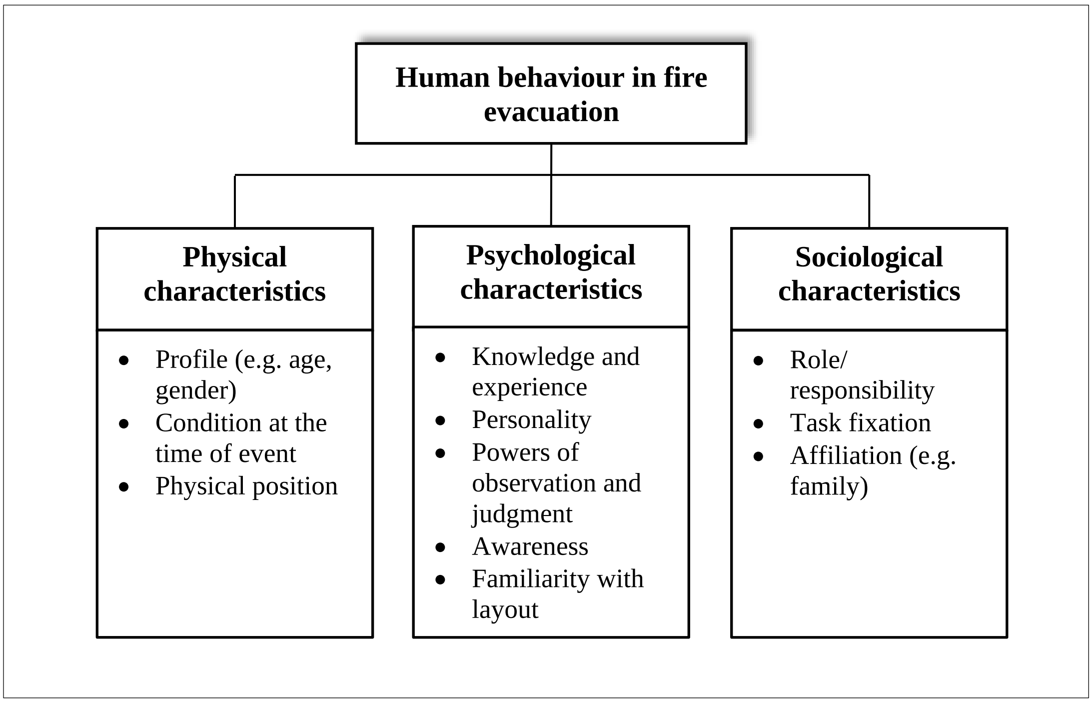

Figure 1.2 Aspects of human behaviour in fire evacuation adapted from Proulx (2001) and Kobes et al. (2010a)

i. Physical characteristics

Physical characteristics refer to the tangible attributes of an individual such as the age, gender, condition at the time of the event such as the disability of the individual and the physical position of the individual (Proulx, 2001). Individuals of varying age and gender may vary in quality and degree of movement (Society of Fire Protection Engineers, 2019). Most of the evacuation models addressed age and gender as the basic physical characteristics of building occupants (Gwynne, Galea, Owen, Lawrence, & Filippidis, 1999).

ii. Psychological characteristics

From a psychological perspective, individuals go through a series of cognitive decision process when responding to fire such as recognition of fire cues, evaluation of available information and formulating response strategies to the fire incidents (Bryan, 2002). Within this decision cognitive process, individual psychological characteristics such as danger assessment, self-confidence, information available, training, experience, knowledge, familiarity and awareness are involved (Vorst, 2010). Meacham (1999) discussed some of the complexities of the human behaviour and the substantial influence of the psychological reactions people have on the evacuation pattern.

iii. Sociological characteristics

An individual's social characteristics are shaped by social structures and identities (Sime, 1995). The interaction among individuals and groups describes the social behaviours. When interactions between people are present, the evacuation will be affected by their roles or responsibilities, task commitment and strong affiliation such as family members (Kobes et al., 2010a).

The study of human behaviour in a fire evacuation began in the 20th century with the earliest research conducted in the 1950s (Bryan, 2002). The traditional model of human behaviour in building fires assume that people are non-thinking agents who will immediately respond to a building alarm and evacuate the area. The researcher at that time assumed that the building had been built safe enough. Hence, the impact of the fire size on the behaviour of building occupants becomes the focus of the research.

With the rapid growth of technology systems, many computer-based evacuation models are being developed and thus improved the ability to understand human behaviour during the process of evacuation. There are a number of studies that review the definition, characterisation and usefulness of the evacuation models (Gwynne et al., 1999; Kuligowski & Peacock, 2005; Santos & Aguirre, 2004; Watts, 1987). In general, evacuation models that take into account the individual behaviour of the occupants are models that allow decisions to be taken by the occupants. Physical characteristics of the human behaviour are involved, such as age, gender and mobility capacity. In some cases, an individual's social interactions or group behavior are considered. Given some pre-defined settings of these factors, simulation on how the different factors influence the fire evacuation can be done. Examples of the well-known existing evacuation simulation models that take into account the aspect of occupant's behaviour are Gridflow (Bensilum & Purser, 2003), building-EXODUS (Owen, Galea, & Lawrence, 1997) and ESCAPES (Tsai et al., 2011). Gwynne, Kuligowski, Kinsey and Hulse (2016) mentioned that in most of the evacuation models, individuals are treated as a population function and are governed by the same style of decision-making process, therefore will react in the same deterministic manner within a group rather than in an individual manner. Thus, the personal attributes such as the psychological aspects which affect decision making and movement process can hardly be examined at individual levels.

Recently, Virtual Reality (VR), a relatively new simulation technology has been used for simulating human behaviour in a virtual representation of a fire evacuation scenario (Arias, Ronchi, Wahlqvist, Eriksson, & Nilsson, 2018; Kinateder et al., 2014; Shaw et al., 2019). In the VR, a reasonably accurate virtual replication of the fire scene is created, and investigators can follow and see the actions of the participants in the virtual environment on a computer screen. The common behaviours observed in the VR are decision-making, exit choice, and sequence of actions performed. The ultimate actions of the participants are likely to be the most important aspect rather than their motivation or psychological distinction since it is hard to be represented and less effectual in the VR environment (Shaw et al., 2019).

In Malaysia, so far, there has been a very minimal study on the human behaviour in a fire evacuation. There are studies conducted to determine the degree of fire safety conditions and motivation factors in evacuating from the perception of building occupants such as in residential colleges in a local Malaysian university (Subramaniam, 2004), Petronas Twin Towers and Kuala Lumpur Towers (Tharmarajan, 2007) and five selected high-rise residential buildings in Malaysia (Yatim, 2009). In all of these research works, the human behaviour is defined from the view of the building occupants itself, mostly the works evolve around identifying factors that motivate occupants to evacuate (e.g. emergency announcement, existing of fire cues or traffic congestion at exit route) and predicting their actions upon exiting the fire events (e.g. use of staircase, follow exit signage or try to fight the fire), while not addressing other aspects of the human behaviour such as the psychological or cognitive aspects that might influence them in making decisions.

Although fire evacuation modelling has gained attention among researchers for a long time, to the best of our knowledge there is a limited research in the area of psychological responses in a fire evacuation and more specifically in Malaysia. Studying the human behaviour in such a context will help researchers to have a better understanding of the decision-making process and thus recommend ways of improving how they may behave effectively and safely in a fire situation.

1.4 Research background

At present, egress tools tend to focus on the representation of physical movement, while, at the same time, over-simplifying evacuee's behaviour in decision-making. The evacuation models have been criticised due to the lack of representativeness of the broad aspects of the human behaviour factor in the models (Gwynne, Kuligowski, Kinsey, & Hulse, 2016; Santos & Aguirre, 2004; Shiwakoti, Sarvi, & Rose, 2008). Among the crucial individual human behaviour aspect that is often incompletely addressed or quantified in the existing evacuation models is the psychological characteristics or the cognitive behaviour that relate how people react in a fire (Cheng et al., 2019; Gwynne et al., 2016; Kobes et al., 2010a; Matellini, Wall, Jenkinson, Wang, & Pritchard, 2013b; Rahman, Mahmood, & Schneider, 2008). Research integrating the psychological parameters in human behaviour modelling and egress movement is extremely limited (Cheng et al., 2019). The lack of these aspects in the evacuation models is due to, in part, insufficient available quantitative research data on all features of human factors (Shiwakoti et al., 2008), and the difficulty in collecting real data of human psychological aspects during fire events (Cheng et al., 2019; Gwynne, 2012b).

The incomplete or limited data regarding human psychological aspects during fire evacuations can be explained by the means of uncertainty problems. From the view of fire analysis, there are two types of uncertainties, the stochastic uncertainty and epistemic or lack of knowledge uncertainty (Notarianni & Parry, 2002). The stochastic uncertainties can be viewed as sources of randomness or variations which result from a stochastic process, while epistemic uncertainties exist because of the lack of complete information about the object or system that is being analysed. An example of stochastic variability is variations in the consequences of one failure incidents to another, and predominantly statistical methods deal with this type of uncertainty. Uncertainty in the estimated value of a model parameter is an example of the second type of uncertainty, and it can be reduced or eliminated by gaining more data or information. The fact that the human behaviour aspect during a fire evacuation is not well represented because of limited knowledge base makes it necessary to be acknowledged as an epistemic uncertainty.

In recent times, the uncertainties in fire evacuation modelling have been represented by risk-based studies. Even though fire remains a rare event, the consequences of such incidents can reach a large extent, which can be treated as a risky hazardous event (Persson, 2002). The quantitative risk-based methods are extensively used, including the Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and Bayesian Network (BN). ETA and FTA are two techniques that provide logical functional relationships among events, i.e. the components and subsystems of a system. FTA is used to analyse causes of failure of systems and the ETA shows the consequences of such an undesired event. Studies that make use of the ETA /FTA in fire-based studies primarily focused on analysing the causes or consequences that are involved in fire operating systems (Chu & Sun, 2008; Guanquan & Jinhui, 2012; Shi, Shuai, & Xu, 2014; Wang et al., 2018). A recent study by Wang et al. (2018) used ETA to simulate evacuation scenarios in a subway fire, where the passenger’s evacuation choices are determined by the fire safety measures (such as the alarm system and emergency routes). Using the survey questionnaire among subway passenger, the probabilities of evacuation scenarios were calculated based on the failure/success probabilities of different control events.

There are two major assumptions of the FTA and ETA. First, the likelihood of events is assumed to be exact and precisely known, and secondly, the interdependencies of events in an FTA/ETA are assumed to be independent. For analysing the high-risk fire safety, the FTA/ETA maybe adequate because of the availability of data and well-established emergency management plan (Matellini et al., 2013b), but seems to be impractical in the human behavioural analysis in which precise data of this aspect are hardly available. While the main characteristic of human behaviour modelling is to capture multiple dependencies among the factors, the second assumption of FTA/ETA is violated. The significant disadvantage of FTA/ETA methods is that they are not able to represent the dependability between events. Hence, FTA/ETA analyses have been demonstrated to deal with stochastic uncertainty by constructing probable fire scenarios in a fire risk assessment but fail to adequately present the epistemic uncertainty and multi-dependencies between factors in fire evacuation modelling. These significant disadvantages of FTA/ETA can be overcoming by the BN approach. The summary of uncertainty in fire-based studies and methods to deal with the uncertainty is presented in Figure 1.3.

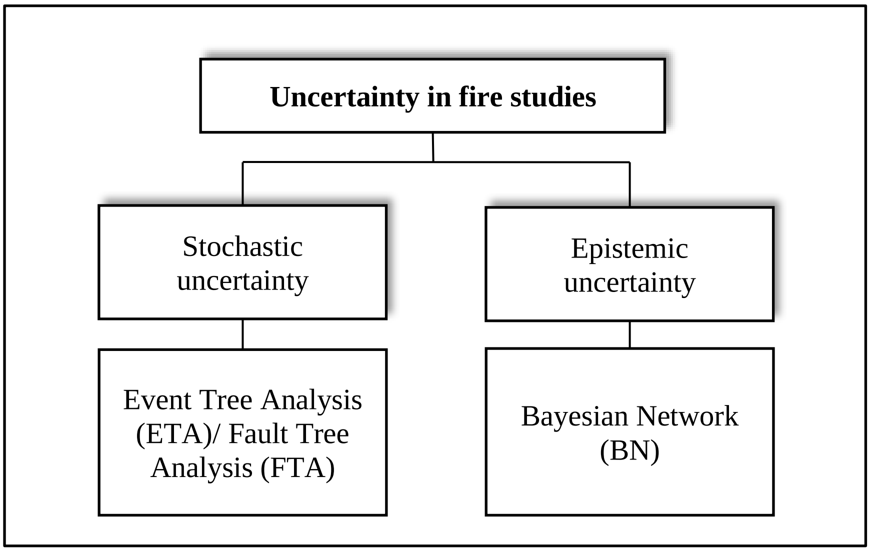

Figure 1.3 Type of uncertainty and methods in fire-based studies

Recently, the BN model has been the preferred choice among researchers in representing uncertain knowledge in risk-based studies (Brooker, 2011). BN provides a powerful framework for reasoning with uncertainty, as referred by Dempster (1990) as "a theory of reasoning from uncertain evidence to uncertain conclusions". The graphical representation of the BN consists of nodes and arcs; where the nodes represent random variables (discrete or continuous variables) and the arcs represent the causal relations between those variables. The benefits of BN are highlighted as follows: 1) effective in modelling situations when data are uncertain, incomplete or partially available, 2) permit to merge knowledge from different sources of data, and 3) does not require a specific distribution type to the data like any statistical technique (Neapolitan, 2008). Furthermore, BN offers a flexible method of reasoning based on the propagation of probabilities throughout the network in accordance with the laws of probability theory (Pearl, 2014).

There are two main phases for BN modelling, the qualitative and quantitative phase (Spiegelhalter, Dawid, Lauritzen, & Cowell, 1993). The first qualitative phase considers the general arrangement of the nodes and arcs of the network structure, which includes the determination of existing knowledge from literature or consulting domain expert that can be synthesised into a conceptual model. The quantitative aspect of the BN is the numerical aspect of the networks, i.e. the representation of the parameter values for all the variables that relate to the structure of the graph. In general, two different methods or a combination of both are used to construct a BN (Zhou, Fenton, & Neil, 2014): 1) automated construction from existing data, and 2) the domain expert-based construction when insufficient or non-existing of empirical data through a procedure called expert elicitation.

Due to data scarcity in human behavior modelling, expert elicitation has advantages in supplying appropriate information through the involvement of domain experts based on his/her past observation, knowledge and experience. In most of the application, the BN model constructed based on input from expert domain where the experts are involved at various stages of BN modelling process. Domain experts are asked to give their opinions on the model structure (variables and the relations between them), estimate the parameter values of variables and evaluate the model (Pitchforth & Mengersen, 2013).

The expert elicitation generally involves the determination of the variables and the strength or relationship of variables in a BN model. The strength is measured by the conditional probability value stored in Conditional Probability Table (CPT) for discrete variables (through statistical point estimates) or conditional probability distributions for continuous variables (through quantiles or variances). Many expert elicitation techniques in obtaining crisp probability values of the BN model are available such as the direct, indirect and CPT filling-up algorithms (Mkrtchyan, Podofillini, & Dang, 2015).

There are also expert elicitation studies that utilise the fuzzy approach by using the linguistic terms to provide the expert's subjective judgments to infer their belief (Kabir, Sadiq & Tesfamariam, 2016; Ren, Jenkinson, Wang, Xu & Yang, 2008; Yazdi & Kabir, 2017; Zoullouti, Amghar & Sbiti, 2017). Generally, the fuzzy approach uses a conversion scale that contains the linguistic terms, e.g. 'low', 'medium' and 'high' with its respective membership functions (MFs) during the elicitation process. Recently, the discovery of the Z-numbers concept by Zadeh (Zadeh, 2011) relates the issue of reliability in decision-making. The Z-number is a 2-tuple fuzzy numbers where the first component is the restriction on the information and the second part is the reliability, confidence or strength of truth of the first component. In comparison with fuzzy numbers, Z-numbers have more capability to describe the human judgment since it includes the reliability of information (Kang, Wei, Li, & Deng, 2012b).

Within the realm of fire safety, BN has been used for undertaking research on fire protection systems (Holicky & Schleich, 2000), modelling of structures under fire (Holicky & Schleich, 2001), human fatalities in fires (Hanea & Ale, 2009), forensic investigation (Biedermann, Taroni, Delemont, Semadeni, & Davison, 2005) and fire spread in buildings (Cheng & Hadjisophocleous, 2011). Research in modelling human behaviour in a fire evacuation through BN framework focuses on the influence of behavioural changes in an individual and group on evacuees' decision-making and actions taken (Hanea & Ale, 2009). The human factors that are included in the models are mostly based on the individuals' physical characteristics, and only a few studies acknowledged the psychological characteristics in predicting the occupant's behaviour. The understandings of the psychological responses that comprise on how these responses relate to each other and what the consequences are in human decision-making, apparently do not involve the related expert in the field such as the psychologists or social scientists.

Hence, considering the advantages of the BN approach in representing the epistemic uncertainty by means of expert elicitation approach, this study intends to develop a new qualitative model and quantitatively measure the psychological response in a fire evacuation.

1.5 Problem statement

The scarcity of database for setting up the networks is the major barrier for applying the BN in the psychological response in a fire evacuation, which necessitates the involvement of the domain expert through the elicitation procedure. The elicitation task from the experts, however, are faced with two major issues, both in the qualitative aspect - domain application of the psychological response during the fire evacuation, and the quantitative aspect - method or technique used for obtaining the parameter values in the model.

From the aspect of qualitative modelling, the existing BN models of the psychological response during a fire evacuation have been found to have a solid literature background of the human behaviour (Matellini, Wall, Jenkinson, Wang, & Pritchard, 2012, 2013a, 2013b; Pires 2005; Radianti & Granmo, 2014), however the process of developing and quantifying the models are mostly not involving the opinion from the domain experts. As supported by Notarianni and Parry (2002) and Cheng et al. (2019), the expert's knowledge of the human behaviour in evacuation modelling remains an uncertainty, particularly in integrating the psychological parameters in the human behaviour models. In order to obtain the best current understanding of the uncertainty problem at hand, opinion from related experts in the field is the favourable option (Tuomisto, Wilson, Evans, & Tainio, 2008). Hence, a new conceptual BN model should be developed by acknowledging the domain experts in the related field of human behaviour area such as psychologists, social scientists and fire safety practitioners.

Meanwhile in terms of quantitative constraints, two issues have been identified. Firstly, studies which apply fuzzy linguistic approach in expert elicitation do not construct the specific conversion scales for fire evacuation domain. It has been observed in many studies of risky events that the conversion scales are either defined by the researcher's own assumptions (Ren et al., 2008; Ren, Jenkinson, Wang, Xu, & Yang, 2009; Ren, Wang, Jenkinson, Xu, & Yang, 2007; Wang, Roohi, Hu, & Xie, 2011; Yu & Park, 2000) or have been adopted from the pre-defined conversion scales proposed by Chen and Hwang (1992) in assisting the experts (Yuhua and Datao, 2005; Charles, Kumar, & Suggu, 2012; Hota, Pavani, & Gangadhar, 2013). However, Cheng and Hwang's conversion scales are too generalized for all problem-solving applications and are not applicable if the experts are familiar with the decision problems (Aldian & Taylor, 2003). To the best of our knowledge, there is no specific conversion scale constructed that is defined by the domain experts for eliciting human behaviour in the fire evacuation area is constructed.

Secondly, the elicitation methods faced the limitation of not taking into account the degree of reliability or confidence of the judgment (Mkrtchyan, Podofillini, & Dang, 2015). When quantitative information is provided, a question may arise as to how certain decisions are made when assigning the value (Azadeh, Saberi, Atashbar, Chang, & Pazhoheshfar, 2013; Brooker, 2011). This question plays an important role in the process of decision-making especially when estimating risky events. Much of the information on which decisions are made is uncertain, and to be useful, information must be reliable (Aliev, Huseynov, Aliyev, & Alizadeh, 2015). To date, no studies have been done to address the uncertainty of information that include the expert's reliability of estimates.

On other hand, the elicitation methods are quite burdensome for non-mathematics experts in providing numerical estimates when eliciting the BN models (Kong et al., 2011). The process of estimating the precise probability value is challenging as people generally have cognitive difficulty in thinking of conditional distributions with several conditioning factors (Morgan & Henrion, 1990). Domain expert such as the fire safety engineers that do not have the expertise in statistics and probability faced the challenge to quantify the BN model since they are usually not proficient in probability theoretical foundation (Kong et al., 2011). Even though many filling-up CPT algorithm has been developed to reduce the number of probabilities to be assessed, up to now far too little attention has been paid in overcoming the difficulties of assigning precise probability values for events, as well as reducing how much expert need to know about probability theory to do so (Kadane & Wolfson, 1998).

Therefore, the goal of this study is to develop a BN model of the psychological response in a fire evacuation from the viewpoint of the domain experts and propose suitable elicitation approaches for its quantification.

1.6 Research question

The research questions can be put forward as:

1. How do psychological characteristics affect evacuation decision under fire events based on expert opinion?
2. How can the conversion scale adequately capture the meanings of the linguistic terms in eliciting the psychological response in a fire evacuation application?

3. How can the elicitation method address the reliability of the expert's judgment and reduce their elicitation burden?

1.7 Research objective

The main goal of this study is to address uncertainties in BN model of psychological response during a fire evacuation through expert elicitation. Specifically, this study includes the following three objectives:

1. to develop a conceptual BN model of psychological response in a fire evacuation
2. to construct a fuzzy conversion scale as an elicitation tool
3. to incorporate the expert's reliability of the judgement in eliciting the developed BN model.

1.8 Research scope

The scope of this study includes the following:

1. Data for analysis is based on expert opinion.
2. Only the human psychological aspects are considered and not the physical and sociological aspects of the human behaviour.
3. For data collection purposes, this study focuses on the psychological responses of a healthy adult person who can self-evacuate from a building.

1.9 Research process

This study is an Applied Statistics research. This study focuses on integrating the existing methods in eliciting a BN model. In the process of the study, a new and unique conceptual model is developed that contributes to the literature in the fire evacuation modelling. In addition, new elicitation approaches are proposed, with a new conversion scale developed as an aided tool for expert during the elicitation exercise. Figure 1.4 presents the whole processes that are involved in conducting the study.

This study starts with a thorough literature review to find potential gaps in fire evacuation modelling. The identified gap reveals that there is a need for developing an expert-elicited BN model of psychological response in a fire evacuation. Subsequently, the methodological framework for expert elicitation studies is developed. It contains a selection of steps and methods that are to be performed throughout the study.

A new conceptual BN model consisting of the psychological factors is developed through theoretical background of human behaviour in fire safety and expert opinion approach. From the model, we developed two different protocols for the purpose of expert elicitation procedure. The first one is the protocol for developing the conversion scale and the other one is the protocol for eliciting the conceptual model, which leads to two sessions of data collection for eliciting both protocols. The data analysis is performed by aggregating the expert's opinions in both elicitation procedures. Then, the result of the analysis is discussed. Lastly, the research conclusion, implications, limitations and suggestion for future work are highlighted.

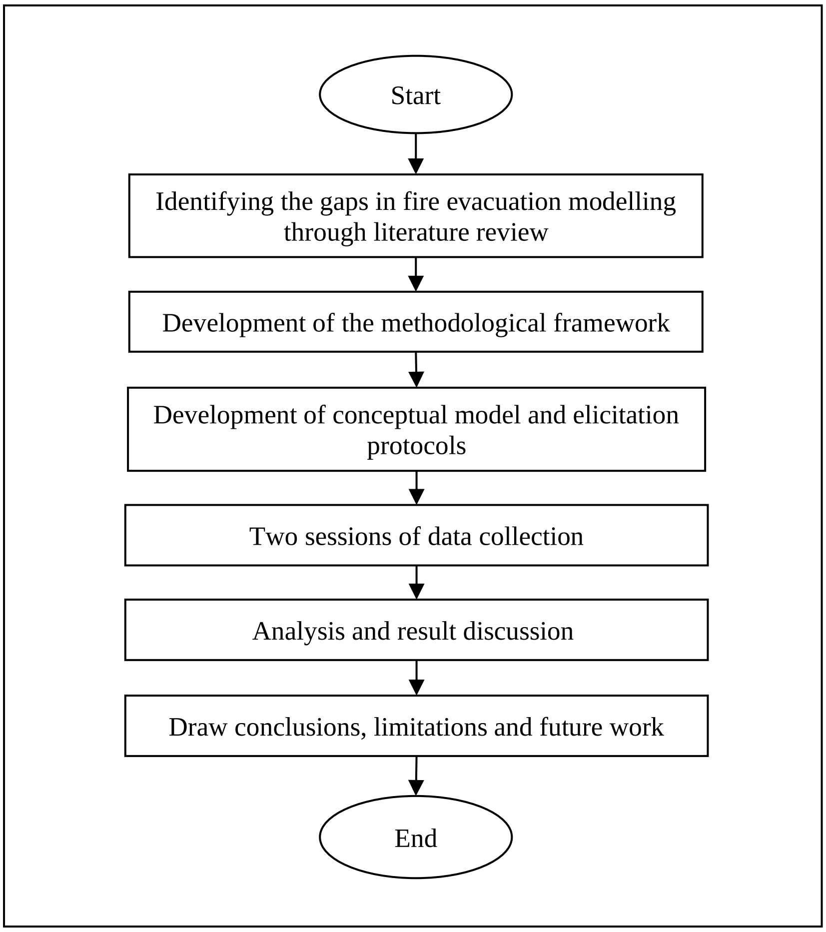

Figure 1.4 Flowchart of research process

1.10 Research contribution

The novelty of this study can be briefly stated in two types of contributions as follows.

Main contributions:

1. The methodological contribution of this study is the implementation of the Z-number concept in eliciting a BN model.
2. The construction of the fuzzy conversion scale for expert opinion exercise.

Others:

1. The development of a BN model of psychological response in a fire evacuation through literature study and expert opinion approach.

1.11 Operational definition of key terms

The operational definitions of the study are as follows (see Table 1.1.):

Table 1.1 The operational definition of key terms

Key terms	Operational definition
Expert elicitation	The process of acquiring the BN model structure (variables and the relations between them) obtaining numerical parameters and evaluating the model through domain experts (Pitchforth & Mengersen, 2013).
Uncertainty	Uncertainty is a general term used to encompass a multiplicity of concepts including lack of knowledge, incompleteness, judgment and variability in a system (Morgan & Henrion, 1990; Notarianni, 2002).
Psychological response	A series of cognitive process when responding to fire such as recognition of fire cues, evaluation of available information and formulating response strategies to the fire incidents (Bryan, 2002).
Fire evacuation	Evacuation is the process in which the people become aware of a building fire and experience a variety of cognitive process/actions before and/or during the movement to a safe place (Society of Fire Protection Engineers, 2019).
Bayesian Network	Bayesian Network is a graphical probabilistic model that depict causal relations between a set of variables, where nodes in the graph represent variables and arcs or edges represent direct connections between the nodes (Jensen, 2001).

1.12 Chapter outline

Chapter 2 of this thesis reviews the current BN models of the psychological response during a fire evacuation in the literature and highlight the fact that there is a need for a more comprehensive representation of the domain expert in the model. This chapter also describes the probabilistic modelling of BN, range of elicitation methods in BN modelling, fuzzy concepts and fuzzification methods available. Chapter 3 describes the methodology of the research in which it covers the expert elicitation procedures in detail. Chapter 4 presents the establishment of a new conceptual BN model and the development of the protocol to elicit the model. The following Chapter 5 presents the procedure to develop the fuzzy conversion scale. Chapter 6 illustrates the feasibility of the framework in eliciting the BN model. Finally, Chapter 7 summarises the general findings and conclusions of the research and provides recommendations for future research.