AN OPERATIONAL RESEARCH-BASED INTEGRATED APPROACH FOR MASS EVACUATION PLANNING OF A CITY

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Large-scale disasters are constantly occurring around the world, and in many cases evacuation of regions of city is needed. ‘Operational Research/Management Science’ (OR/MS) has been widely used in emergency planning for over five decades. Warning dissemination, evacuee transportation and shelter management are three ‘Evacuation Support Functions’ (ESF) generic to many hazards. This thesis has adopted a case study approach to illustrate the importance of integrated approach of evacuation planning and particularly the role of OR/MS models.

In the warning dissemination phase, uncertainty in the household’s behaviour as ‘warning informants’ has been investigated along with uncertainties in the warning system. An agent-based model (ABM) was developed for ESF-1 with households as agents and ‘warning informants’ behaviour as the agent behaviour. The model was used to study warning dissemination effectiveness under various conditions of the official channel.

In the transportation phase, uncertainties in the household’s behaviour such as departure time (a function of ESF-1), means of transport and destination have been. Households could evacuate as pedestrians, using car or evacuation buses. An ABM was developed to study the evacuation performance (measured in evacuation travel time).

In this thesis, a holistic approach for planning the public evacuation shelters called ‘Shelter Information Management System’ (SIMS) has been developed. A generic allocation framework of was developed to available shelter capacity to the shelter demand by considering the evacuation travel time. This was formulated using integer programming. In the sheltering phase, the uncertainty in household shelter choices (either nearest/allocated/convenient) has been studied for its impact on allocation policies using sensitivity analyses.

Using analyses from the models and detailed examination of household states from ‘warning to safety’, it was found that the three ESFs though sequential in time, however have lot of interdependencies from the perspective of evacuation planning. This thesis has illustrated an OR/MS based integrated approach including and beyond single ESF preparedness. The developed approach will help in understanding the inter-linkages of the three evacuation phases and preparing a multi-agency-based evacuation planning.

Keywords: Agent-Based Models, Integer Programming, Warning Dissemination, Evacuee Transport Management, Evacuation Shelter Information Management

DEDICATION

This thesis is dedicated to my *parents, my Guruji, all my beloved teachers, and lovely friends.*

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CHAPTER ONE: INTRODUCTION

1.1 **Need for research**

Environmental disasters are constantly occurring throughout the world. The recently published 'World Risk Report' (WRR - 2012) states that "*The balance sheet for the ten years from 2002 to 2011 is alarming: 4,130 disasters, over 1million dead and economic losses of at least 1.195 trillion US dollars"* (Beck et al. 2012). For the same level of threat, the impact on the community could be very different in different regions and preparedness has a role in reducing this impact. For example, a 6.3 magnitude earthquake (2011) in New Zealand claimed 187 lives and 16 billion USD losses. On the other hand, a higher magnitude earthquake of 7 Richter units in Haiti (2011) claimed 220,000 lives and 8 billion USD losses (WRR - 2012, p 4). The ability of the society to respond to these disasters is contingent upon the public's capacity to face and respond to it, the 'Emergency Management Authorities' (EMA) preparedness in mitigating these disaster impacts and developing disaster plans. The focus of this thesis is not on the way evacuation decision (whether and when to evacuate) is made by Government Organisations (GOs) rather on evacuation performance after the decision to evacuate.

1.2 **Disaster Definition**

"*Disaster is a crisis situation that far exceeds the capabilities*" (Quarantelli as cited in CYEN 2012) of both the public to continue normal life and the emergency responders. The following are two definitions on Disasters as given by World Health Organisation (WHO) as found relevant to this thesis:

- *A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources (ISDR).*
- *Situation or event, which overwhelms local capacity, necessitating a request to national or international level for external assistance (CRED).*

Disasters are caused by an agent/hazard - either 'natural or man-made or a combination' - by seriously impacting the community. This disaster agent/hazard is defined as "*a threatening agent or probability of occurrence of a potentially damaging phenomenon within a given time period and area*" (IFRC 2012). Table 1.1 presents some of the key hazards as classified by EM-DAT (IFRC 2012) and it is not an exhaustive list. Within these disaster agents, the environmental hazard can be further classified into two types (UNEP 2012, p4) – ‘ongoing and rapid/sudden onset’ (refers to disasters occurring in a short time frame) and ‘slow-onset/creeping’ (refers to incremental but long-term and cumulative environmental change).

Table 1.1 List of key hazards (Data source: IFRC 2012 as cited from EM-DAT)

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1.3 **Disaster Statistics**

Table 1.2 summarises key disasters that occurred around the world in a six month period between June and November-2012. The table highlights a typical impact of large-scale disasters. Disaster statistics of key events show that when a large-scale disaster strikes a community as large as 5 million people (August 2012 flood in Pakistan) could get impacted, some of them become homeless and inevitably to be evacuated. The means of evacuation could also get impacted during a disaster (e.g. Metro Manila flooded during flood and landslides June 2012) thus making evacuation to safety more difficult and delayed. The impacted population move to shelters, which are generally large safe buildings, such as relief camps (India October 2012), schools (Benin October 2012) and with host families (Cameroon August 2012). Even shelters identified at the planning stage could get damaged during disaster as the case in Hurricane Sandy in October 2012.

Table 1.2 Key disaster events between June-2012 and November-2012 only relevant information (synthesised from ReliefWeb, 2012)

Disaster	Country/Location	Impact summary
Drought (Nov-2012)	Sri Lanka	Estimated 1.8 million people impacted due to second consecutive season with scanty rainfall and drying of natural reservoirs.
Tropical Storm Nilam (Oct 2012)	India	Tropical storm Impacted states in Southern India, displacing 150,000 people and about 68,000 people are sheltering in 86 relief camps.
Tropical Storm (Oct-2012)	Philippines – Son-Tinh	About 15000 people evacuated to 27 shelters, killing 27 people and destroying 200 houses
Hurricane Sandy (Oct 2012)	Bahamas, Cuba, Panama, Haiti, Jamaica, Panama United States of America (USA)	Affected 1.8 million, killing 60 people and impacting 18000 homes. Up to 18,000 people in temporary shelters were affected by Sandy and 5,800 shelters were damaged or destroyed.
Floods (Oct-2012)	Republic of Benin in West Africa	Over 10,000 people have been displaced and reside in schools and other institutional buildings or in makeshift camps in the open air. It is unclear when the flood waters are likely to subside.
Wild Fires (Sep-2012)	Ecuador	2900 wildfires destroyed over 15500 hectares of land and also caused interruption of water supply to 4000 people
Earthquakes (Sep 2012)	China	Two earthquakes of magnitude 5.7 and 5.6 Richter scale in Yunnan and Guizhou provinces caused 100,000 people to be evacuated, killing 60 and injuring 50.

Tropical Storm Isaac (Aug-2012)	Haiti, Dominican Republic, Cuba	**Haiti:** 15000 people evacuated and 335 homes destroyed **Dominican Republic:** 4700 houses flooded and 2225 people took shelter in evacuation centres
Earthquake (Aug-2012)	Indonesia	A 6.2 Richter scale earthquake shook the eastern Indonesian island of Sulawesi, killing six people and damaging 1097 houses. Limited road access to earthquake victims has disrupted the delivery of relief supplies to the area.
Tropical Storm Kai-Tak (Aug – 2012)	Philippines, Vietnam, China	**Philippines:** Flash floods due to heavy rains killed 7 people, 86700 people were affected and 10650 people took shelter in 77 evacuation centres. **Vietnam:** Intense rain and strong winds killed 27, 12000 houses damaged and 23000 hectares of cropland flooded. **China:** 530,000 people estimated to be evacuated. About 4200 houses destroyed and 17300 damaged.
Floods (Aug-2012)	Cameroon	The rains and floods have destroyed or damaged many houses, leaving about 25,000 people homeless. Most of these have found shelter with host families, but 5,000 have sought refuge in school premises.
Earthquake (Aug-2012)	Iran	Rural villages in North-western Iran were impacted due to twin earthquake killing 306 people, injuring 3000 and about 16000 left homeless.
Typhoon Haikui (Aug-2012)	China	In Jiangsu province, about 180,500 people were relocated. In Anhui province, about 26000 people were evacuated. In Zhejiang province about 4452 houses were destroyed and damaged.
Floods (Aug-2012)	Chad	In Rig Rig district about 3000 people were in need of shelter. In Sila region, 13000 houses were affected and the flood blocked major humanitarian supply routes.
Floods (Aug-	Pakistan	Intense monsoon rain and floods impacted 5 million people. About 270,000 people are housed in 478 relief

2012)		camps.
Typhoon Darmey (Aug-2012)	China	Lianoning Province, about 1.46 million were affected, about 17000 houses were damaged and about 13800 people were forced to evacuated.
Tropical Storm Saola (Jul-2012)	Philippines and China	In Philippines about 16,000 took shelter in 73 evacuation centres. In Fujian region of China, 300000 people were evacuated.
Earthquake (Jun-2012)	China	In Xinjiang province, a 6.6 magnitude earthquake destroyed about 7500 houses and damaged 64000 houses, resulting in evacuation of 48000 people and impacting 155,000 people.
Flood and Landslides (Jun-2012)	Bangladesh	Flash floods and landslides in Eastern Bangladesh caused 110 deaths and affected more than 400,000 people. Due to landslides low-lying areas were inaccessible in Chittagong. About 290,000 people were evacuated to 602 shelters.
Flood (Jun-2012)	DPR Korea	Heavy rain and resulting flood damaged infrastructure in nine provinces. A total of 62,889 people were affected by the floods, with 3,589 houses destroyed, 3,236 houses damaged, and 12,031 houses submerged.
Floods and Landslides (Jun-2012)	Philippines	In Northern and Central Luzon, about 4.4 million people were affected, over 1 million were displaced, 1.2 million were living with relatives and friends while 135,308 people were residing in 431 evacuation centres across the affected areas in Luzon as of 31 August. Infrastructure including Metro Manila was also flooded.
Flood (Jun-2012)	South Sudan	In Upper Nile State, Jamam camp, home to 120,000 refugees from Sudan's Blue Nile State, was flooded and relocated to a new site in Gendrassa. Many roads within Abyei were flooded, restricting the possible return of people displaced from the area and hampering the movement of humanitarian actors.
Flood (Jun-2012)	India	Due to monsoon rains, about 900,000 people were forced to leave their homes in the state of Assam.

For more information on disaster statistics pertaining to these key events and other disasters, readers are directed to EM-DAT (http://EMDAT.be) or ReliefWeb (http://reliefweb.int) websites. Even though all the hazards (Table 1.1) impact the community resulting in death, injury or disruption to their lives, evacuation is a response option only for some. This thesis pertains to evacuation planning for disaster situations that would lead to risking life of population when they continue living in their community, and hence take protective measure by relocating temporarily (evacuation) to a safer location.

1.4 **Evacuation Definition**

Evacuation helps in "*transferring people from risky areas to safer ones*" (Perry and Lindell 2003). "*Evacuation, regarded as a critical course of action to relocate people and property, helps to alleviate loss of life and property to a great extent*." (Chen et al. 2012, p207). This section explains various terms used in the evacuation literature. Safeguarding - both the public and households - can influence the level of economic loss due to a disaster. However, relocation of property is not considered within the scope of this thesis. This thesis pertains to evacuation planning of household population from region(s) of a city due to a disaster and not investigating evacuation from a building or a facility (e.g. football stadium, stations, etc).

A large-scale emergency in city can risk lives of the households. In general, government with the involvement of various organisations both public and private (henceforth collectively as Emergency Management Authorities – EMAs) are legally responsible for preparing disaster response. Figure 1.1 presents disaster cycle with four phases (Alexander 2009, p5) and the following bullets present brief definition of these terms (Altay and Green 2006, p480). This four-cycle approach for comprehensive emergency management is widely used (Altay and Green 2006).

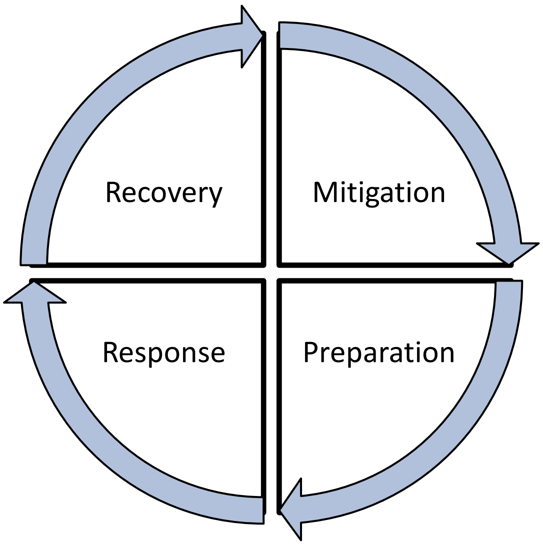

Figure 1.1 Four-phase disaster cycle (simplified and reproduced from Alexander 2009, p6)

- *Mitigation* is the application of measures that will either prevent the onset of disaster or reduce the impacts should one occur.
- *Preparedness* activities prepare the community to respond when a disaster occurs.
- *Response* is the employment of resources and emergency procedures as guided by plans to preserve life, property, the environment, and the social, economic and political structure of the community.
- *Recovery* involves the actions taken in the long term after the immediate impact of the disaster has passed to stabilize the community and to restore some semblance of normalcy.

Readers are directed to look at Altay and Green (2006, Table 2, p481) for comprehensive list of activities in each phase. It is important to look at evacuation planning as one of the key activities in the cycle rather than in isolation, and two examples are presented here as an illustration of this perspective. The infrastructure prepared for disaster mitigation could be impacted during a disaster and subsequently the evacuation could happen with an impacted support system/infrastructure (Sorensen 2000). For example during floods in the Sila region of Chad (August 2012) major humanitarian supply routes were blocked. A community in the recovery phase after a recent emergency might be less prepared for another evacuation. The disaster phase of the population will impact the next evacuation. Such dynamics indicate the need for looking at planning within four phases of disaster cycle and not in isolation. These dynamics could be identified as planning scenarios of impacts on critical infrastructure and further formulate evacuation plans. Understanding household responses during evacuation is fundamental to city-scale evacuation planning.

Household evacuation responses

During a large-scale emergency some of the city regions may be affected due to a disaster. The households have variety of response during an emergency depending on the scale, type and timeline of the disaster. Table 1.2 highlighted some of the recent disasters where the houses were damaged and may become unsafe to live. In such situations, these households need to relocate till their houses are deemed safe to live and hence may require 'relocation' to long-term accommodation in relief camps. Some of the houses may not be warned during emergency and even after warning they may choose to 'stay in-situ'. In some cases of nuclear accident, staying closed doors (stay in-situ) is a key response option. In cases of flash flooding for a short duration, household response could be to move to higher floors ('vertical evacuation') or evacuate to a pre-identified safe-location within the neighbourhood ('horizontal evacuation') typically in a walk-able distance. Vertical evacuation during tsunami or flash flood assumes that higher floors of the building are safe for the level of disaster impact (Little et al. 2007). In many cases the household need to 'evacuate' out of the danger area and return when declared as safe. The safe location could either be one of the public shelters identified by the government or a private destination (friends, family) outside the evacuated zone.

When the household's departure is late during rapid-onset disasters, evacuees put themselves at risk for their safety. It was reported that about 75.7% of fatalities (Haynes et al. 2009, p291) during flash floods in Australia occurred when people were en route to safety. There is growing interest on sheltering-in-place for flash floods, due to its short warning time and rapid onset of disaster.

Evacuation zones around nuclear power plant are chosen depending on the likely scale of the nuclear incident and the subsequent plume behaviour. A Nuclear Regulatory Commission in the United States (US-NRC) classified two evacuation planning zones (US-NRC, 2012) around nuclear facility namely 'plume exposure pathway zone' (10 mile) and 'ingestion exposure pathway zone' (50 miles). Such 'zone classifications' for a planned evacuation scenario will help the authorities to estimate the endangered population and inform their preparedness efforts. The individual zone could map to any administrative unit (municipality) or specific classification for a hazard. A household in the disaster impact zone need to be notified by the authorities of an imminent threat or after an impact and advice on emergency response. Some of the households may choose not to comply with evacuation order. Such diverse options at the household level are to be factored in the evacuation plan.

In a complex disaster situation, some of these household response options are combined depending on the endangered zone. Personalising the impact on the household level will have influence on the evacuation response. For example, a forecasted storm flood due to torrential rain may result in flooding the low-lying areas and they may need evacuation. For other regions that are at higher elevation, households may adopt vertical evacuation or stay indoors. There are various types of household evacuation response choices available for the EMAs.

1.5 **Types of evacuation**

'Preventive evacuation' (or precautionary evacuation) is carried out 'prior to' actual occurrence of a predicted event and depends on the time window available from the evacuation decision to evacuees reaching safety (Alexander 2009, p151). 'Post-disaster evacuation' (or no-notice evacuation) is carried out when the disaster has already occurred, deeming it necessary for the households to evacuate immediately as a protective measure (Chiu et al.2007). Here, some of the households may already be warned directly by the disaster event and others need to be notified of the emergency situation.

'Staged evacuation' is a plan of identified order/sequence of evacuating zones, beginning with the most vulnerable population and progressively suggesting a timeline for relatively lower vulnerable people (Chien and Korikanthimath, 2007). This vulnerability is often attributed to the proximity with the hazard epicentre indicating the earliest impacted zones. By staging evacuation, the household's departure time is staggered based on the vulnerability level and thus the load (e.g. vehicle volume) in the infrastructure (e.g. evacuation road network) is reduced.

'Shadow evacuation' is referred to "*spontaneous evacuation by people outside of any official declared zones*" (US-NRC, 2012). During Hurricane Floyd, about 35% of 2 million evacuees who did not have to leave evacuated and thereby contributed to enormous congestion in Houston (Wolshon 2006, p33). Such evacuees are referred in literature as 'shadow evacuation'. Some households might perceive heightened risk of disaster impact. When some of the neighbour zones/regions are evacuated and not theirs, the household might evacuate even though not needed. The role of EMAs in forecasting the likely impacted and also evacuated zones, and communicating it to the regions (including non-evacuated zones) would alleviate unnecessary fear that leads to shadow evacuation.

Depending on the condition of the hazard impact, evacuation may not be an option at all. "*A major fatality in flash floods is attempted evacuation in a vehicle*" (Sorensen 2000, p120) as the evacuation time (ET) window is short and untimely/late departure can place the evacuees in serious danger like directly facing the flood. For example, when there is nuclear plume release in the atmosphere due to accident, the evacuees may have to stay indoors and remain fully closed. Evacuation during that circumstance may not be advisable. On the other hand, when it is life-threatening due to acute level of nuclear release the household may be advised to evacuate from the vicinity as a safer option. It is important for the evacuation planners to identify and design scenarios for planned threats. Such dynamics form as an input for EMA's 'evacuation decision' (whether to evacuate or not?) based on forecasted impact, only some/all of the zones may be evacuated.

1.6 **Mass evacuation planning and management - Overview**

Evacuation is a temporary relocation of population from endangered zones to avoid impact due to a disaster (Cabinet-Office, 2006). EMAs plan, prepare, exercise, train and respond to a disaster. In the context of evacuation due to emergency (natural or man-made disaster), the role of EMA preparedness initiatives in a complex disaster situation is inevitable. Not all disasters require evacuation as a response. Understanding about the phases in evacuation is the foundation for designing EMA level plans for supporting evacuation.

"*Japan is one of the few top-end-risk countries that have an effective warning and evacuation system, as well as excellent community education programme*" (quoted from an article by Nakano et al. (1974) as cited in Parasuraman and Unnikrishnan 2000, p26). A massive 7.7 Richter Niigata earthquake in 1964 caused damage to 20000 houses and resulted in 16 deaths along with injuring 315 people. "*Due to the quality of its preparedness programme*" the level of mortality was very low (Parasuraman and Unnikrishnan 2000, p. 26) during the Niigata earthquake. Though the quote is about four decades old, the impact of all the preparedness initiatives and their effectiveness needs a review, given the recent events in Fukushima disaster. The 2011 disaster in Japan had large-scale impact due to the compounded catastrophes namely earthquake, subsequent tsunami leading to a power shortage and then the nuclear accident in Fukushima. In order to study large-scale evacuation planning, it is important to understand the phases of household evacuation. The following paragraphs provide examples from disaster statistics in order to 'identify and briefly introduce phases of evacuation'.

A fire broke out in the midnight (26-November-2009) in a residential sub-urban area Peckham in London and about 310 people self-evacuated by alerting each other. There was no death during this accident. One of the evacuees stated in a media report, "…*knocking on all the doors of my neighbours to alert them*" (Randhawa and Lydall, 2009). Official warning of evacuation order is disseminated to notify the endangered households of an imminent or ongoing disaster. Peckham sub-urban evacuation is an example where there was no official evacuation warning but the public were helping themselves to safety. A new national emergency alert system is currently under development in the United States called PLAN (Personal Localised Alerting Network). This will require a special chip to be fitted in mobile phones to receive official alerts (Merrett, 2011). Once a decision to evacuate is made or when the disaster has already struck, the endangered areas are warned for evacuation. Dissemination of warning message is the first phase of evacuation.

During the evacuation of Hurricane Katrina (2005) about 100,000 evacuees had no access to transport and did not evacuate (Tate 2010). Evacuees use various means of transport namely cars, metros, evacuation buses and by foot to physically move from place of danger to safety. The physical movement of evacuees in evacuating vehicles often referred using the term 'evacuation' is the second phase. The safe location or destination is referred as 'shelters' which is the third phase.

During the fire accident in a processing plant in Nanticoke (1987), a midnight evacuation order was issued and about 2000 of 15000 evacuees sought to mass care shelters (Stambaugh, 1987). Over half a million of residents in the regions of Miyagi prefecture and surrounding regions in Japan were evacuated for weeks during the tsunami (April-2011) and subsequent disaster in the Fukushima nuclear power plant in Japan. About 2.6 million people from 14 districts were affected by flooding due to continuous rainfall in West Bengal, India (August 2011) leading to the death of 27 people and large-scale abandonment of flooded residence to makeshift shelters (NDTV, 2011). In such circumstances, EMAs have inevitable responsibility of providing shelters to these impacted households. The following section presents a brief overview of fundamental aspects of mass evacuation planning.

Evacuation from building facilities, aircrafts, stadium, railway stations and housing complex happens from restricted boundary/spaces (e.g. building floors), the evacuees are warned of a danger and leave the premise (generally by foot) until it is deemed safe for return. Building evacuation, though an interesting research problem, is not considered within the scope of this thesis. The term ‘evacuation’ in this thesis refers only to a scale of ‘region(s) or whole city’ evacuation due to a natural or manmade disaster.

The primary purpose of evacuation is to ensure the safety of the population in case the disaster strikes. “*Two essentials of this are warning and evacuation*” (Alexander 2009, p146). In the literature often the word ‘evacuation’ is used to refer to the ‘transportation’ phase of emergency namely movement of evacuees from the place of danger to safety. EMAs based on the disaster forecast and monitoring of condition, make ‘evacuation decision’ and issue an order to evacuate (warning and informing). For implementing evacuation plan, households require various forms of support for evacuating to safety. “Evacuation support functions” (ESF) as defined in the thesis are response roles of GOs in implementing the evacuation plan and supporting the household to evacuate. From warning to safety, there are three ESF phases namely

- ESF-1 warning dissemination (to disseminate the evacuation decision to the public),
- ESF-2 transportation (to support and provide evacuating households use evacuation network to reach their safety) and
- ESF-3 sheltering (to accommodate the evacuees needing public shelter as their destination during the evacuated period).

Each ESF is typically managed by different organisations. The organisation-level evacuation plan enlists ESF’s role and tasks during evacuation. The thesis specifically focuses on the three ESFs that are common to many hazards.

1.7 **ERGO Project Overview**

ERGO (Evacuation Responsiveness by Government Organisations) project was funded by the European Commission under the Directorate-General Justice Freedom and Security (JLS/2007/CIPS/025). This thesis is focused on identifying how the EMAs use analytical models to prepare for mass evacuation. There were 10 countries namely Belgium, Denmark, Sweden, Germany, Spain, Iceland, Bulgaria, Poland, United Kingdom and Japan. Ergo countries have nominated a senior level emergency manager to be a part of International advisory board (IAB) panel to oversee the project.

Figure 1.2 presents the ERGO team's integrated framework to be adopted for planning mass evacuation. The ERGO team proposed the integrated approach to planning mass evacuation as an overarching framework for planning mass evacuation. This framework would facilitate multilevel agencies to plan, train and exercise their design scenarios of mass evacuation. The focus of the project is to look at these six phases of evacuation and this thesis specifically contributes to phases 4-6 (Figure 1.2), and the remaining phases are covered by two researchers.

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Figure 1.2 Integrated approach for planning mass evacuation proposed by the ERGO project (Shaw et al. 2011a, p16)

1.8 **Examples of OR models**

'Operational Research or Management Science' (OR/MS) is defined "*as a scientific approach to decision making, which seeks to determine how best to design and operate a system, usually under conditions requiring the allocation of scarce resources*". OR/MS has been widely used in various phases of emergency (Altay and Green 2006). This thesis focuses on generating model-based understanding of evacuation phases, its inter-relationships and further developing an integrated approach for large-scale evacuation of regions of a city. "*Inefficiencies in planning translate very easily into loss of life, injuries or damage that could have been avoided*" (Alexander 2009, p5). This summarises the inevitable need for EMAs to design evacuation plans for ‘planned threats’ and have confidence in their response capabilities through preparedness metric. There are various methods in OR/MS that have been used in evacuation planning including optimization, simulation [agent-based modelling, discrete event simulation (DES)], cellular automata, and decision support systems. This thesis has chosen simulation and agent-Based modelling as the chosen technique. Details of OR/MS methods and the justification of choice of methodology are presented in Chapter 3.

1.9 **Aim and Objectives of the thesis**

The aim of this thesis is to evaluate how ‘evacuee behaviour-based large-scale evacuation planning of a city can be supported using OR/MS models?’ The objectives of the thesis are:

- To understand evacuation phases and the dimension of evacuee behaviour that will affect overall evacuation effectiveness
- To demonstrate how mass evacuation preparedness can be supported through integrated approach encompassing the three phases by using computer-based OR models.
- To develop computer-based simulation models for the phases of mass evacuation namely warning message dissemination, evacuee transportation model and shelter management by incorporating the public behaviour in the analytical models.
- To support evacuation planning from 'warning to safety' using OR models.

The following are the research questions addressed in this thesis

- Q1: What is the need for modelling ESFs'?
- Q2: How do household evacuation behaviours impact different phases in evacuation?
- Q3: How do household evacuation behaviours affect organisations' evacuation response plans?
- Q4: How OR-based approach can help GOs in evacuation planning?
- Q5: How OR-based approach can provide an integrated evacuation planning environment?

1.10 **Thesis outline**

This thesis is organised into eight chapters. Chapter 2 presents analyses of literature grouped into three ESFs namely warning dissemination, transport, management and emergency accommodation. This chapter provides in-depth analyses of literature specifically looking at ‘the existing OR/MS models, household behaviours and identified research gap’ for three ESFs.

Chapter 3 presents the research methodology available for modelling evacuation and analytical techniques are presented in the first section. The next section presents the overview of the ERGO project and the ERGO city case study. The chosen ABM and case study approach is justified in the next sections. This chapter ends with how the models were validated in this thesis.

Chapter 4 presents the findings on warning dissemination (ESF-1) from ERGO countries followed by gaps identified in this thesis. Development of an Agent-Based Model (ABM) warning dissemination including official channels and household as informants (unofficial channel) is described for a prototype model of 1000 houses and then for the city scale. The chapter ends with sensitivity analyses of various model parameters, simulation experiments and chapter conclusion.

Chapter 5 presents the findings on transportation management (ESF-2) from ERGO countries followed by gaps identified in this thesis. Development of household behaviour-based ABM transportation model with evacuation using 'car, pedestrian and bus' is explained for the city scale. The chapter ends with sensitivity analyses of various model parameters, simulation experiments and chapter conclusion.

Chapter 6 presents the findings on shelter management (ESF-3) from ERGO countries and followed by gaps identified in this thesis. Development of a holistic approach for evacuation planning is presented, followed by a generic model using Integer Programming (IP) for zone-wise allocation of shelters. In the concluding section, sensitivity analyses of household shelter choice behaviour household behaviour are studied using experiments with the allocation model.

Chapter 7 presents a zone-wise overview of evacuation performance of ERGO city and identifying interconnectedness of phases based on the model results. Over the ESF level evacuation plans, the need for integrated approach of evacuation planning is presented.

Chapter 8 reviews the research questions addressed in various chapters. The next sections present discussion on the contribution of thesis to literature, further scope of research and implications to practitioners. Concluding section of the thesis summarises reflection on PhD experience.

CHAPTER TWO: REVIEW OF LITERATURE

2.1 **Evacuation planning – An introduction**

The focus of this thesis is on the evacuation planning phase of an emergency. From the point of view of hazards, there are two broad approaches for emergency planning namely all-hazards approach and disaster-specific approach. Quarantelli (1991, p97) believed that "*it appears that the generic approach is most applicable in the emergency phases and somewhat less so in the mitigation phase*". A generic all-hazards approach is preferable "*as it achieves greater levels of protection and economies of scale"* (Alexander 2009 p95).

EMAs often prepare for many hazards and design evacuation scenarios for each relevant threat to inform their evacuation response plans. Given the cost-effectiveness (Alexander, 2009) and wide applicability (Quarantelli 1991), this thesis adopts an all-hazards approach for developing large-scale evacuation models. The impact on ESF response capabilities due to the disaster needs to be ascertained for each hazard scenario and further their evacuation response plans need to be evaluated.

With increasingly complex disaster (e.g. 2011 Great East Japan earthquake), it is desirable to identify key threats for the planned area and design scenarios for evacuation planning. Firstly, EMAs could have generic evacuation plans common for all hazards for supporting evacuation. Evaluate the generic plan and build specific scenarios and responses for the identified threats and also complex disasters envisaged based on the experience.

2.2 **What is Emergency preparedness?**

One of the four stages of disaster cycle is preparedness (Figure 1.1). "*Emergency preparedness means taking action to be ready for emergencies before they happen. The objective of emergency preparedness is to simplify decision making during emergencies*" (US-NRC 2012). "*Inefficiency in emergency planning translates very easily into loss of life, injuries or damage that could have been avoided*" (Alexander 2009, p5). Preparedness initiatives are taken by the emergency responders at the planning stage of a disaster planning cycle to formulate each organisation's response strategies to the planned threat in-case of eventuality. These are "*actions taken in anticipation of an emergency to facilitate 'rapid, effective and appropriate' response to the situation"* (Inter-Agency Contingency Planning Guidelines for Humanitarian Assistance 2001) as stated in WHO (2012). "*Preparedness* *measures can take many forms including the construction of shelters, installation of warning devices, creation of back-up life-line services (e.g. power, water, sewage), and rehearsing evacuation plans*" (CYEN 2012).

From the EMA perspective, an evacuation response is defined as "*the set of actions conducted during the initial impact of these emergency situations, including those to save lives and prevent further property damage providing emergency relief to victims of natural or man-made disaster*" (Barbarosoglu and Arda 2004).

This thesis will study the potential for supporting three ESFs preparedness for large-scale emergency using OR models. There are other evacuation supporting roles beyond evacuees reaching safety (see definition of Barbarosoglu and Arda, 2004), which even though interesting will not be considered within the scope of this thesis. Readers can refer to Altay and Green(2006) and Caunhye et al. (2012) review articles on 'Disaster Operations Management' (DOM) which covers ESFs including and beyond evacuation, to name a few, relief and humanitarian logistics, search and rescue operation, managing the supply chain for shelter operations (e.g. food, medicines, etc) and providing medical and social care for the evacuees. This thesis only covers the ESF preparedness between 'Warning households to reaching safety'. The EMAs use various measures for supporting their evacuation plan.

The following are common preparedness measures (CYEN 2012, p6) for the ESF:

- communication plans with easily understandable terminology and chain of command
- development and practice of multi-agency coordination and incident command
- proper maintenance and training of emergency services
- development and exercise of emergency population warning methods combined with emergency shelters and evacuation plans
- stockpiling, inventory, and maintenance of supplies and equipment

'Evacuation Preparedness Assessment Workbook' (Shaw et al. 2011b) has identified operational tasks for the EMAs to evaluate their preparedness. This workbook's sections are aligned to the ERGO evacuation framework as presented in Chapter – 1. Ohio (2012) has devised a similar Preparedness assessment tool (Ohio, 2012) called "citizen evacuation and shelter-in-place". Apart from workbook-based evacuation preparedness assessment, models are also used in evacuation preparedness. The next section will present brief introduction about the OR/MS and subsequent section will be on the models already used in evacuation planning.

2.3 **Operational Research and evacuation planning**

The definition of OR/MS has been presented in Chapter 1 (p30). In general, formal computer models are often a simplified representation of households in evacuation planning areas and further study the evacuation performance under planned threat scenarios. Evacuation planning of highly likely impacted environment based on expected disaster intensity could be studied in an evacuation model. The role of OR/MS models could prove vital for the EMAs to evaluate before-hand evacuation plans and strengthen their preparedness. OR/MS is widely used in different phases of emergency (Altay and Green 2006). This section looks at how OR and analytical modelling techniques can help emergency planners to support their analysis of evacuation. There are many OR techniques that are used in the planning for evacuation management, and the following are few important OR methods.

Optimisation is the use of mathematical modelling to find an ‘optimum solution’. It is used when the problem can be formulated in a quantitative manner with predefined structures. Optimisation techniques are widely used in traffic management for obtaining optimum evacuation routes for the evacuees (Chiu et al. 2007). Here the roads are represented as networks and the evacuation route is obtained for minimum travel time.

Simulation modelling is the use of a computer-based representation of reality to study the changing behaviour of a system under different conditions. Simulation modelling allows the user to explore what-if scenarios, test the robustness of systems, experiment with different configurations and policies, and understand complex interdependencies between critical incidents.

Agent-based modelling (ABM) is a type of simulation technique used mainly in social science, where the evacuees are represented as agents and defined using behavioural properties (e.g. response time) to measure the interaction among the other evacuees (agents) in order to obtain the overall behaviour. ABM has been used to study pedestrian evacuations from underground stations (Castle, 2006) as well as for planning evacuation of the city (Chen et al. 2006). In both the cases the evacuee behaviour is represented using ‘agents’ for developing the model. "*Multi-agent simulation is defined as a computational model for simulating the actions and interactions of autonomous individuals with a view to assessing their effects on the system as a whole*" (Taubenbock et al.2009, p1522). "*An agent-based model is a computational method for simulating the actions and interactions of autonomous decision-making entities in a network or system, with the aim of assessing their effects on the system as a whole. Individuals and organisations are represented as agents*" (Dawson et al.2011, p172).

There are many more OR techniques available in literature and key simulation techniques are compared in Chapter – 3. There are models developed by combining various techniques to take advantage of each modelling approach. For example, in order to distribute evacuees from different regions to safe areas, a 'spatial multi-objective optimization problem' (Saadatseresht et al. 2009) was formulated by combining the GIS model into multi-objective algorithms for evacuation planning. Critical infrastructure Modelling system (CIMS) is a DES model to study the interdependencies of various infrastructures and identify evacuation response strategies (Santella et al. 2009). A combined simulation and optimization model has been developed for evacuation planning of Ocean City, Maryland, United States (Zou et al. 2005). This model has been developed to test evacuation planning in advance and also as a system to support real-time operational decisions. A survey of OR models and its application to evacuation management can be found in Caunhye et al.(2012), Simpson and Hancock (2009), Wright et al.(2006), Altay and Green (2006) and Pidd et al.(1996).

"*Social science studies reveal that most socio-behaviour features of disasters are not agent- or class-agent- but are generally similar for different types of natural and technological agents*" (Drabek 1986 as cited in Quarantelli 1991, p98). Hence developing an all-hazard approach that includes household behaviour is argued in this thesis as a suitable approach. The objective of this thesis is in studying the household dynamics for each of the phases 'warning to safety' for a preventive evacuation during rapid-onset disasters using OR/MS models in order to support collective EMAs preparedness.

2.4 **Need for models in evacuation planning**

Emergency managers from various organisations are involved in developing evacuation plans for their local hazard scenario. These plans are to be aligned with the other factors like legal restriction, availability of resources (personnel and equipment), demographic details of the population, type of hazard and its potential impact. GOs as a part of a preparedness initiative should identify evacuation response strategies. Evacuation models are purpose-built simplified representations of a city or regions of a city. The models can serve as a platform for testing and experimentation (Pidd et al. 1996, Green and Kolesar 2004, Simpson and Hancock 2009) of the evacuation plans, various response policies, simulating worst-case scenarios and identify potential for further capacity development.

Computer models are, '…well able to represent dynamic aspects of change' (Gilbert and Troitzsch 2005, p13). In evacuation modelling, the dynamics of the disaster event (e.g. flooding) and its impact on the evacuation (e.g. road network disruption) can be represented conveniently as a computer model to support the decision makers. The robustness of the evacuation plan can be tested by harnessing the dynamic capability of the computer models. Thus modelling approach would serve as low-risk approach of testing compared to experimenting in real-life.

Evacuation plans have assumptions about the evacuee behaviour (e.g. choice of evacuation transport) that forms the basis for evacuation response plans (Drabek 2007). The uncertainty in the assumed evacuee behaviour and the implication of these assumptions will impact the successfulness of evacuation. Some of the key model insights are "*the latest possible start time of evacuation, the best evacuation routes or the most suitable traffic management measures*" (Pel et al. 2010, p102). OR models could serve as a platform for the GOs to understand the implication of evacuee behaviour assumptions on the overall evacuation. The uncertainty of the evacuee behaviour is generally studied in the model using the sensitivity analysis of the evacuation performance.

Using models: a health warning

Evacuation models are abstract representation of the reality. Given the complexity of the disaster event along with the abstraction in the model, could lead to less reliable model results. An over-reliance on a model's results, understatement of assumptions and ignoring the context-specific aspect on interpretation of the output results are some issues highlighted as reasons for failures of models in emergency management (Starbuck 1983, French and Niculae 2004). A carefully designed modelling approach needs to factor in these issues to make the model reliable for the intended purpose. This highlights the need for validation of the evacuation models in order to increase their reliability in evacuation planning.

2.5 **Validation of the model**

The Emergency Managers using software models in evacuation planning need to know about two broad classification of software products namely 'off-the-shelf (OTS) models' and 'custom-built models'. OTS product is ready to roll the minute you slide the installation CD in the drive, low priced, generic built and has revisions for updates (Voas 2002, Morris 2010). An example of OTS product used in evacuation planning is NAME – Nuclear Accident Model - developed by UK Meteorological Office (Maryon et al. 1991) and used to predict the dispersion of nuclear plume given the atmospheric conditions like temperature, wind speed, etc. On the other hand, Custom-built Models are developed in house with tailor-made specification, generally expensive and includes organisation-specific features. For example, 'Crowd Dynamics Inc.' (Crowd-Dynamics, 2010) developed an agent-based simulation model to understand the external crowd movements of a stadium in Solna (Sweden) for planning the entrance and exit routes.

Some OTS products have generic features that can be customized to the evacuation planning area. For example, GIS software like ArcGIS can be used for a wide range of purpose including evacuation modelling. Irrespective of the type of model used in evacuation planning, the end-users need to know about the underlying principles of the model, limitation, scope and various assumptions. This understanding will help in validation of the model and increasing the end-user confidence.

There are four stages of modelling process namely *conceptual Modelling, model coding, experimentation and implementation* (Robinson 2003, p. 52). The conceptual model is defined '…*as a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model*'. From the conceptual model stage, the description is converted into software codes or components that comply with the intended objective. Once the model has been coded and tested, the model requires experimentation to study the variation of input and output along with stability of the results. Quality or reliability of the model '…must be built in every portion of the software development process' (Pressman, 2001). End-users when they are involved in the model development will have better idea of scope, assumptions and principles in comparison to OTS models.

The validity of a simulation model can be evaluated in three ways (Garson 2009, p274):

1) *Outcome validity* is obtained by comparing the results from the simulation model with real-world results to ascertain the accuracy of the model results. In the evacuation modelling obtaining real-world data is limited hence doing outcome validation is considered difficult.
2) *Process validity* is used to demonstrate "*that the process that leads to outcomes in a simulation corresponds to processes in the real world*" (Garson 2009, p275). Evacuation models are required to be aligned with various stages of the evacuation process and the internal sequence of events need validation.
3) *Internal validity* demonstrates that simulation software validly represents the process being modelled along with the explicit statement of assumptions. For ascertaining the internal validity of the models, the evacuee behaviour, organisational response plans and assumptions need to be accurately represented.

Even when the empirical data of evacuee behaviour are limited, quantification and simulation using models would outweigh the potential problems regarding the external validity of the models (Größler 2004). These validity tests help in measuring the reliability of the models to ensure the validity and acceptance of model usage for the intended purpose.

2.5.1 Data sources in evacuation planning

In evacuation modelling, quantifying the behaviour of evacuees is important and can affect the acceptability of the model by the end-users. Evacuee behaviour modelling can be done through different types of data collection namely post-evacuation survey, pre-evacuation stated preference survey, social sciences literature, practitioner experience, post-disaster reports, etc. Table 2.1 summarises these techniques and their key features.

Table 2.1 Different sources of obtaining evacuee behaviour data and its key features

Data collection technique	**Key feature**	**Examples**
Evacuation preference surveys conducted pre-evacuation	Evacuees are sent survey questionnaire based on a scenario and evacuees respond to these questions. Evacuees may not act the way they say. In some cases detailed interviews are conducted to know how the evacuees will behave in case of evacuation. The drawback in this method is that the evacuee’s actual behaviour may be different from the response.	Bird et al. (2009), Jóhannesdóttir and Gísladóttir (2010
Post-evacuation survey	After the evacuation, the evacuees are contacted to obtain how their evacuation experience was. This data will help in ascertaining how the successfulness of the evacuation and also to obtain lessons learned. These surveys rely on the evacuees’ ability to recollect and share their actual experience.	Brodie et al.(2006)
Social science literature	Evacuee behaviours based on the previous disasters are used to formulate generalisable theories which can support evacuation plans.	Drabek (1996)
Practitioner Experience	The knowledge from practitioner experience is held at key individuals within GOs. This needs to be documented and disseminated across agencies.	
Post-disaster report	GOs prepare reports after a major disaster event to reflect on the successfulness of their response as well as to obtain generalisable lessons.	Pitt (2008)

For example, in order to evaluate transport plan after the Hurricane Katrina, authorities used “*traffic volume and speed data, traffic videos, media accounts and interviews of evacuees*” (Wolshon 2006 p28). As a part of preparedness initiative for Hurricane evacuation in the United States, Federal Emergency Management Agency (FEMA) has conducted research with the public at the local county level. These behaviour analyses data form the basis for evacuation plans specifically on *‘sheltering analysis, transportation analysis, guidance in emergency decision making and public awareness efforts’* (FEMA, 2010).Thus GOs as a part of preparedness initiative could collect data about the evacuee behaviour from the available sources for their planning area and test evacuee behaviour uncertainties using the OR models.

2.6 **Levels of Modelling**

Evacuation models can be developed at different levels depending on the smallest unit of analyses and purpose of modelling. There are three levels namely micro-level models, macro-level models and meso-level models (Pidd 1996).

- 'Micro-level models' are used to study individual entities (define entities and give examples) in the road network using simulation from the evacuation zones to safer destination (Pidd 1996). In micro-simulation the individual entities are treated independently and the interaction effects are generally discarded (Gilbert and Troitzsch 2005).
- 'Macro-level models' do not track the individual entities in a detailed level instead aggregate the individual entities from the same evacuation zone as a group and study the overall evacuation behaviours.
- 'Meso-level models' is a middle-line approach between other two categories and track individual as groups or packets of vehicles but at a more detailed level compared to macro-simulations.

Table 2.2 Different levels of models

Model details	**Level of model**	**Reference**
NETSIM – Traffic simulation model	Micro	Rathi and Santiago, 1990
A behaviour based simulation model	Micro	Stern and Sinuany-Stern (1989)
Network simulation model for dam failure	Macro	Southworth and Chin, 1987
MASSVAC – Evacuation time estimation	Macro	Hobieka and Jamie, 1985
PACKSIM – real time traffic management	Meso	Barcello and Grau (1993)
CEMPS – Configurable Emergency Management and Planning System	Meso	Pidd (1996)
ArchSIM – multi-agent model for opportunity driving behaviour simulation in urban road junctions	Micro	Doniec et al.2008
Dynamic traffic assignment model (DTA) to study moving bottlenecks	Meso	Juran et al.(2009)
ABM based micro-simulation of urban traffic networks	Micro	Lopez-Neri et al.2010
DTA model using DynaMIT for congested traffic in a megacity (Beijing, China)	Meso	Ben-Akiva et al.(2012)
Multi-agent Transportation Simulation – MATSim	Micro	http://www.matsim.org/
TUNAMI-EVAC1 – Tohuku University's Numerical Analysis for investigation of near-field Tsunami (TUNAMI) tool's evacuation module	Micro	Mas et al.2012a

Table 2.2 presents the classification of different models available in evacuation literature. When EMAs need to manage people leaving facilities such as an underground station, shopping malls and stadia, there are many types of micro-level crowd modelling software such as VISSIM, EXODUS and MYRAID. For example, the Jamarat bridge pilgrimage facility in Hajj (Makka) has been modelled using mathematical models (Algadhi and Mahmassani 1990) as well using ABM software (Crowd-Dynamics 2010) for better management and to avoid overcrowding. This model was used to identify bottleneck within the system that slows down the overall exit time and streamlining it when there is multidirectional flow of crowd. Kerridge et al. (2001) provide more information on a detailed review of pedestrian modelling. Representation of households in the modelled area requires a different model development units compared to facility evacuation models.

ABM is a social simulation technique that specifically looks at how the individual behaviour and their interactions will affect the overall behaviour of the system. ABM has been widely used in evacuation modelling of building facilities (Castle 2006) and regions of a city (Rogers and Sorensen 1991). For evacuation models in ABM, the behaviour of agents (e.g. a household) can be specified as 'rules' based on the process observed in the real-life evacuation situation. For example, each household can have attributes set to reflect its characteristics (e.g. access to warning channels like TV/radio) and behaviours (e.g. the need for public shelters), and these can be programmed as the properties of the agents.

A detailed comparison of different levels of simulation techniques and its features is available in Gilbert and Troitzsch (2005, p13). The readers are cautioned about a different usage of terminology in evacuee transport modelling, where micro-level refers to tracking individual vehicles, meso-level refers to stream of vehicles and less detailed individual vehicle tracking and macro-level refers to the traffic flow (vehicles/hours) from different sub-regions of the city. Thus depending on the level of detail and the purpose of the model, EMAs could choose the appropriate modelling level for developing the model.

In practise, EMAs use these measurements to set operational targets for their evacuation response plan. For example the 'Shearon Harris Nuclear plant' board decided a policy to notify 100% of the population within 5 miles surrounding the plan area within 15 minutes (Sorensen 1992). Here, the 'notification target' (100%), 'warning priority zone' (5miles) and the ‘warning time target’ (15 minutes) are quantitative variables used as an operational performance measure.

An evacuation model is generally used to measure evacuation performance for the simulated threat. This requires identification of key performance indicators (KPIs) for each ESF and collecting the values during the model run-time. The literature on KPIs for ESF is presented in the respective sections.

2.7 **Purpose of the models**

OR models have been used in all the four phases of emergencies namely Mitigation, Preparedness, Response and Recovery (Altay and Green 2006). Models 4-6 of the ERGO project looks at how analytical tools are helpful for ensuring the emergency preparedness and hence this review will focus on the OR applications in the preparedness stage only. Application of OR in large-scale evacuation modelling can be broadly classified as: disaster specific models; evacuation support models. The evacuation support models are discussed respectively in the three ESF sections.

Disaster-specific models

Disaster-specific models are also used as a forecasting tool to predict the potential areas to be evacuated and the timeline of when the disaster would strike. These models help in supporting the evacuation decision during the event. These models are developed by the respective scientific discipline and generally maintained by the lead organisations. For example, flood models are used by environmental agencies (or their equivalent) to predict the flood level during a disaster event. Table 2.3 (adapted from Altay and Green 2006, p482) highlights some references for various ‘disaster-specific’ OR models.

Table 2.3 Disaster-specific OR models (adapted from Altay and Green 2006, p482)

Disaster Type	**Reference**
Earthquake	Viswanath and Peeta (2003)
Flood	Wei et al. (2002), Dawson et al. 2011
Storm surge – SLOSH model (Sea, Land and Overland surges from hurricanes)	Zhang (2008) and SLOSH (2010)
Nuclear incidents	Barbarosogulu and Arda (2004), Ozdamar et al. (2004), Ishigami et al. 2004
Tsunami	Charnkol and Tanaboriboon (2006); Mas et al. 2012a
Wild fire	Simard and Eenigenburg (1990)
Glacial flooding model	O'Connor and Baker (1992)
Snow avalanches	Schweizer et al. 2003
Oil and chemical spill	Wilhelm and Srinivasa (1997)

The outputs of these disaster-specific models are used for identifying the evacuation zones, impact level of the disaster and when the zones will be affected. For example, SLOSH model (sea, lake and overland surges from hurricanes) provides levels of storm surge for various combinations of hurricane strength, forward speed of storm and direction of storm. SLOSH model is used for real-time forecasting of surges from approaching hurricanes in coastal basis in the United States. The focus of this thesis is evacuation planning not for a particular disaster. Wright et al. (2006) provide more information about disaster-specific OR models. Apart from these two purposes of model, the model can also be used as public awareness generation tool. For example, 'Stop Disaster' is an online game developed by UNISDR (Stop-Disaster 2012) for school children to generate awareness on disaster impact on the communities due to tsunami, flood, hurricane, wild fire and earthquake.

2.7.1 Models for evacuation support function

Apart from the disaster-specific models, there are OR models used in the preparedness stage to develop and test the evacuation plans as well as identifying the relatively best strategies among the available options. The integrated framework proposed by the ERGO Model of evacuation shows six tasks in large-scale emergency planning for which the GOs prepare themselves and the public. This framework has been used as a basis for classifying the OR models used for EMA preparedness. The disaster-specific models summarised above can help in understanding the evacuation zone (ERGO Model 2) as well as making the evacuation decision (ERGO Model 3). There are also OR models that can help in planning the warning dissemination (ERGO Model 4), evacuee transport planning (ERGO Model 5) and emergency accommodation management (ERGO Model 6). The next three sections (2.2 to 2.4) will discuss the literature associated with these three phases.

Evacuation Timeline

The previous section highlighted the various aspects that will affect when the evacuees receive the evacuation order. It is important to understand the sequence of events for managing the evacuation. Figure 2.1 represents the four separate components of events during the evacuation based on the definitions provided by Urbanik et al. (1980) as cited in Southworth (1991, p19). This classification is from the perspective of EMAs in evacuation phases.

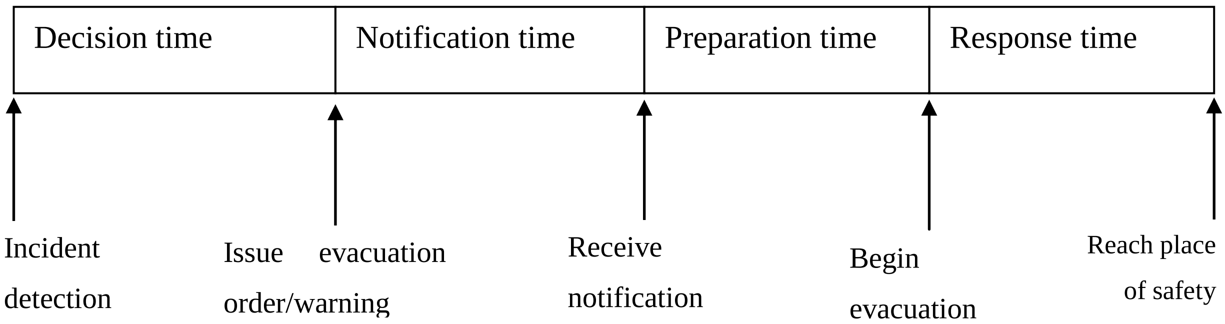

Figure 2.1 Components of evacuation process from 'evacuation decision making' to 'evacuation to safety'

Southworth (1991, p.19) defines terms that underpin Figure 2.1 :

- *Decision time* is defined as the time between incident detection and an official decision to order an evacuation.
- *Notification time* is defined as the time required notifying all the individuals in the area at risk of such an evacuation order.
- *Preparation time* (or mobilisation time) is defined as the time required for individuals to prepare to evacuate the specified area.
- *Response time* (or clearance time) defined as the time required for individuals to physically travel to safety.

Evacuation planning is one of the key tasks in the preparedness phase of a four-phase disaster cycle and one of the main foundations for the field of Disaster Operations Management

(DOM). "*DOM is by nature multi-organizational, but organizations are only loosely connected leading to managerial confusions and ambiguity of authority*" (Altay and Green 2006, p484). This comment highlights a need for multi-organisation centric approach for evacuation planning rather that restricting to organisational level only or at times transportation.

In infrastructure such as EOC (Emergency Operation Centres), Multi-organisational decision making already exists to serve as Evacuation Decision Support System. Even though the individual organisations respond to specific tasks pertaining to an evacuation phase/phases, all their concerted efforts contribute towards successful evacuation. 'However, is there a system that provides a common platform for evacuation planning across organisation to analytically support their multi-agency response? Do these organisations base their evacuation plans on interrelationships between ESFs?' To answer these there is a need to relook at the ESF phases from the perspective of evacuation plan and household behavioural choices of evacuees.

2.8 **Evacuation warning message Dissemination**

This section of the chapter will focus on the first ESF i.e. Warning message dissemination. The section begins with understanding of basic literature on evacuation warning and dissemination process, then the literature review of two major channels of warning (i.e. formal and informal channels) and modelling warning dissemination process. The section ends with summary of findings from the literature review and gaps for further research in this thesis.

Introduction to Warning Dissemination

Warning systems 'warn' the public under threat before/during an evacuation and some 'inform' them of actions to carry out to protect themselves and others. The need for quick dissemination of warning message is essential for no-notice disasters like earthquakes, tsunamis, flash floods, tornadoes, industrial accidents and terrorist attacks. Importance of warning channels for rapid-onset events like tsunami has been highlighted after 2004 Earthquake in South Asia (Samarajiva 2005; McCloskey et al. 2008). For example, during a preventive evacuation of a flash flood in Germany (August 2002), two upstream villages were warned by the television news of the onset of severe rain, yet, across those two villages only 29% and 22% of residents managed to evacuate (Parker et al. 2009).

Although for these residents it would take a short time to evacuate to safe ground, evacuation efforts were compromised by a lack of official warning within a reasonable time, a loss of power supply, and various breaches in flood defence affecting evacuation routes. In this case, the official warning system did not have enough warning coverage and hence, did not suitably support the public in protecting themselves from harm. Effective warning and informing helps to save lives.

What is Early warning system?

An UNEP report on the state of art and future direction defines early warning as "*the provision of timely and effective information, through identified institutions, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response*" (UNEP 2012). Early warning system (EWS) comprises systems and process that enable "*risk analysis, monitoring, and predicting location and intensity of disaster; communication alerts to authorities and to those potentially affected; and responding to the disaster*" (UNEP 2012, p3). Sorensen (2000) offers a dual definition of a warning system: "(a) detects impending disaster (b) gives that information to people at risk and enables those in danger to make decisions and take action" (p119). This thesis focuses on the second aspect, namely, the transmission of the warning message to households at risk. By linking the Sorensen's definition with UNEP on EWS, it can be observed that sub-systems of EWS can be broadly grouped into (a) detection and (b) dissemination.

During 2011 Earthquake in Japan the EWS was activated in 8 seconds after the detection of tsunami P-wave, and tsunami warning to the public was issued after 3 minutes of the earthquake (Mas et al. 2012a, p42). In the case of tsunami, various end-to-end warning systems cover many aspects such as "*tsunami hazard and vulnerability assessment, perception studies, evacuation modelling, etc*" (Taubenbock et al. 2009, p1510) and Table 2.4 summarises examples of such systems used in different geographies.

EWS covers events from the forecasting of disaster to the deliverance of warning of a rapid-onset events or slow-onset events. It includes forecasting techniques and also organisational communication. The role of organisational structure from the level of decision makers to the grass-root level (general public) cannot be understated. Timely and accurate forecasting is the foundation of 'effective warning information' delivered to the public. This thesis focuses on warning channels (communication means) that deliver disaster/threat information to the general public and specifically on the role of localised networks in warning dissemination.

Table 2.4 Tsunami warning systems around the world

Warning system	Reference
US NTHMP – 'National Tsunami Hazard mitigation system' in the eastern pacific	Bernhard 2005, Titov et al. 2005
UrEDAS – 'Japanese Urgent earthquake detection and alarm system' in the western pacific	Saita and Nakamura 2003 as cited in Taubenbock et al. 2009
GITEWS – 'German Indonesian Early warning system' in the Indian Ocean	Lauterjung 2005 as cited in Taubenbock et al. 2009

What is warning effectiveness?

Effective warning during the large-scale emergency situation is essential for saving lives, by ensuring that the maximum proportion of population is well-informed about the threat. Miscommunication of the severity of the emerging flood warning message has been cited as one of the main reasons for the estimated death of about 10,000 people in river flooding in West Bengal (India) (Schware 1982, p. 210). The warning dissemination being the first stage of alerting the public will have cascading impact in the subsequent evacuation phases. This requires understanding of the warning dissemination process.

2.8.1 Warning dissemination process

Williams (1964) as cited in Schware (1982) has given a six-step process for evacuation warning as represented in Figure 2.2. These steps, though proposed for flooding, are generic and believed to be applicable to all other emergencies. This framework depicts the interconnectedness of various aspects of warning dissemination and this could provide an overall basis for designing warning dissemination plan. The preparedness of the public (Figure 1.2, Model-1) would have an impact on 'how the warning message is perceived', leading to their evacuation response. The role of evacuation decision making of GOs is elaborated in 'making the evacuation decision' (Figure 1.2, Model-3), from which the evacuation order (warning) is issued to the public. This section presents the literature findings on warning dissemination process from the stage of evacuation order to the beginning of evacuation (Figure 1.2, Model-4).

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Figure 2.2 Six-step process for warning (Williams, 1964).

'*Warning system should integrate social factors that affect public response to warnings and to understand its effectiveness*' (Schware 1982, p211). This reinstates the need for context-specific message content that is pre-tested with the public. For a social science perspective of warning system, refer to McLuckie (1970). For pre-testing of the warning content the GOs could understand the individual response of the warning message and this has been modelled as a cognitive process (Lindell and Perry 1992) for flood warning.

Sorensen (1991) studied the household dynamics of departure time using a post-evacuation study conducted after 1987 Nanticoke hazardous material fire accident (United States) and following were the conclusions based on quantitative estimates using factor analysis. The study also concluded that the factors 'perceived threat, age and family size' were not related to the mobilisation time.

Table 2.5 Household attributes and factors affecting them (Sorensen 1991)

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In contrast, the post-evacuation study in Niigata (2004) found that elderly people due to their difficulty in mobility were killed (Tamura et al. 2006). The evacuees with difficulty in mobility - even though comprising less proportion in the overall population - are more vulnerable and needy from the first responder. As cited by Sorensen (1991, p156) "*Older* *people are less likely to hear a warning than middle-aged or younger people*". The EMAs as a preparedness initiative could identify areas where there are high proportion of senior citizens and people under social-care live in order to provide additional support during emergency. This entails a need for the lead organisation to work in collaboration with other agencies (e.g. senior and disability clubs).

To know more about the individual behaviour during large-scale emergencies refer to Miller (1992). This thesis focuses on a household's warning behaviour as the unit of analysis and not on individual micro-behaviour. GOs planning for the warning dissemination need to factor in the '*emergency details*' - nature of the threat, location, guidance, time and source of the hazard - and also ensure the '*message contents*' using style aspects like specificity, consistency of message across channels, accuracy, certainty and clarity (Sorensen, 2000).

There are two phases within the warning dissemination process namely *alert* and *notification*. 'Alerting' is defined as *the ability of emergency officials to make people aware of the imminent danger and seek more information* (Rogers and Sorensen, 1991). 'Notification' is defined as *the interpretation of the warning message leading to appropriate evacuation response behaviour* (Rogers and Sorensen 1991). "*An extensive literature exists on how individuals and families interpret and respond to such warnings when they are received.*" (Sorensen and Mileti 1987). There is enough literature (Sorensen and Mileti 1987) on designing an evacuation message content leading to the desired evacuee response (notification). The alerting phase would depend on the 'means' (i.e. warning channels) of reaching the public about the emergency situation, and this phase will be the focus of the thesis.

2.8.2 Warning dissemination systems

Warning and informing systems comprise official warning channels and unofficial warning channels. "*Official systems are usually characterised by formalized, staged warning and communication process, involving a management hierarchy, an inter-agency liaison structure through which communications are transmitted and procedures for warning the public is implemented*" (Parker and Handmer 1998, p46). Examples of official/formal channels are sirens, television, radio, text and pre-recorded messages to landlines/mobiles, mass messaging systems (e.g. UMS - unified messaging service) and door-to-door knocking by officials. The effectiveness of these depends on the timing of the day (Stern and Sinuany-Stern, 1989) and the availability of the channel (Parker and Handmer 1998, Sorensen 2000).

"*Unofficial warning systems are processes whereby people warn those within their personal networks – whether this be within a government agency, those within other bodies or communities or those within their own communities*" (Parker and Handmer 1998, p47). The unofficial warning channel is also described as a 'contagion process' where-by 'people hear the message and then sequentially tell others' (Rogers and Sorensen 1991).

The National Steering Committee on Public Warning and Information, United Kingdom (NSCPWI 2003) has classified the official warning systems into:

- *audible systems* (e.g. sirens, tannoys, route alert)
- *telecommunication systems* (automated caller systems, emergency phone diallers, bulk messaging service)
- *mass communication systems* (broadcasting through television, radio and ham-radios)
- *verbal information* (door-to-door knocking by officials)

In the literature various names are used to refer the warning message dissemination with the public as *informants*, like unofficial systems (Parker and Handmer 1998), informal systems (Sorensen 2000), 'people-to-people' (RedCross 2005), folk and personal systems (Schware 1982, Werrity et al. 2007). The following section provides an overview of the features of various official warning channels and its limitations.

Official warning channels

Each public warning method has pros and cons as presented in Alexander (2009, Table 5.3). This will be helpful for the warning planners to choose channels during evacuation and also plan evacuation scenarios with availability of official channels.

Table 2.6 highlights the important features as well as the limitations of various official warning channels. It can be noted that no single channel can cater all the public groups and hence a combination of the available channels is essential. Although there are official warning channels that are technologically sophisticated (e.g. mass broadcasting systems) for the general public, people with visual and hearing disabilities become more vulnerable during the disaster as they are not easily reachable using official channels.

As official warning system comprises combination of channels, the effectiveness of each channel will impact overall warning effectiveness. The effectiveness of official warning channels has been researched using simulation models to build findings that have practical relevance to emergency planners (Stern and Sinuany-Stern 1989, Rogers and Sorensen 1991, Southworth 1991). The effectiveness of each channel is represented as a time series value of cumulative houses warning (Sorensen 2000, Figure 1, p122). As one house can receive warning from more than one channel and the receiving of first warning message from any channel makes the house warned. Whether the house has access to the warning channel (e.g. with or without mobile)? Are they connected to the channel at the time of warning (e.g. TV may be switched off in night while sleeping)? The household's attributes can affect whether a particular channel can reach that household.

Table 2.6 Characteristics of warning channels

Warning channel	Feature	Limitation
Sirens	Low cost. It has many sophisticated designs like electronic siren, sirens with voice capability and remote activation capabilities	People don't pay attention to it and people don't understand the meaning of different sounding signals (Sorensen 2000) Electronic sirens with voice capability can fill this gap (Sorensen 2000); an example for this is Telegrafia (2010)
Tone alert radio	Personalised warning mechanism and remote operation (ASC 2010)	Needs electric power through battery and needs dedicated system installation and support
Media channel – radios	One of the important media channel especially suitable to alert people who are driving	The percentage of radio listeners depends on the time of the day and also on the activity of the evacuee during dissemination
Media channel – television	Video and voice to give elaborate warning message. Easier to give constant updates	Depends on the TV viewing patterns (Sorensen 2000), and there are models studying the diurnal variation (Tavakoli and Cave 1996)
Mobile phones	SMS text alert as well as voice-based alert to the subscribed users	Requires collaboration with the telecommunication service providers

Warning channel	Feature	Limitation
Mass dissemination systems/EBS – emergency broadcast systems	‘Auto-dial’ feature for reaching large number of telephones in minutes	Requires dedicated system installation and support which are expensive
Landline telephones	Auto-dialling systems predominantly use landline-based alerting	Only the evacuees who are in their house are likely to be reached in the channel
Media channel – internet	Social media and news feeds are increasingly popular source of warning dissemination (Sutton et al. 2008). For example, AlertSU is an emergency alert system integrated mass-communication systems with Facebook and Twitter feed in Stanford University area (San Francisco Bay) for earthquakes (Julian 2010)	Public need to be connected to the service and also depends on the internet network availability. With increasing use of ‘smart phone’, this channel has the potential for including formal warning plans to reach the internet users
Door-to-door knocking	Personalised warning dissemination to each household by first responders (generally police). It is considered to be effective due to reliability of the warning source	During the emergencies, the availability of resources for door-to-door knocking is limited by the availability of number of personnel (Sorensen 2000)

Roger and Sorensen (1991) classified the location/activity of the household for different time into five fundamental activities namely:

1. Home asleep
2. Indoor at home or in the neighbourhood
3. Outdoors in neighbourhood

4. In transit
5. Working or shopping

The study also used a time series of activity profile for the modelled area (Roger and Sorensen 1991, Figure 2, p125) and this data could be used in evacuation planning to develop scenarios. A threat/disaster event itself becomes a warning and is referred to as ‘natural warning’ in the literature (Muhari et al. 2012). For example in the case of tsunami, “*a receding wave at the shoreline*” (Muhari et al. 2012, p91) could serve as a signal for impeding tsunami and serve as a warning. It would be risky for the authorities to allow the natural warning as the only channel to be relied upon, as only the households that noticed the signal would be warned. For wide dissemination of warning message, the authorities use official channels to disseminate during an event.

Hygo Framework for Action 2005 – 2015 (UNISDR, 2006a) calls for developing “*early warning systems that are people centred, in particular systems whose warnings are timely and understandable to those at risk*”. The warning system need be socio-technical systems in order to reach the public leading to a quick evacuation response based on the EMA’s warning. During the rapid onset of flood*ing, “the most commonly affected groups are those who are mobile at the time of flood”* (Werrity et al. 2007, p3) and this mobile group cannot be reached by some of the official channels (e.g. TV, landline numbers) and rely on certain channels such as radios and text alert. Subscriber-based alert system like ‘Flood Watch’ can help only for the signed-up users, and the transient population, tourists and visitors are generally more vulnerable. Thus providing timely warning to the transient population and the tourists continues to be a challenge for the GOs. Thus the official warning channel forms a critical portion of the warning dissemination plan.

Public with various disabilities are more vulnerable to receiving warning messages. Special telephone devices and strobe lights are used for warning people with hearing disability (Sorensen, 2000). ‘CAP-ONES’ is an emergency notification system that provides an approach of modifying warning message to different users and devices (Malizia et al. 2009). The proposed approach uses an open standard called ‘Common Alerting Protocol’ and tailored it for devices used by disabled people to receive messages. Evacuation warning plans require special procedures to reach the vulnerable population. More often the social network of these disabled groups could be the first source of information about an emergency. The role of social network among these disabled groups is even more crucial in warning dissemination. Based on the literature reviewed, warning dissemination to the vulnerable people requires further investigation and the practitioners need to include this category in their evacuation plan.

Unofficial Warning channel

No official channel can reach all the people during the warning phase due to various vulnerabilities of the warning channel to failures, effectiveness of the channels used, etc and hence "*one must rely on word of mouth for warning the residual population*" (Alexander 2009, p147). Even though the official channels form major portion of the formal warning dissemination process, the unofficial warning channel cannot be ignored. Parker and Handmer (1998) addressed the importance of unofficial communication (including personal network and direct observation) during floods. The personal networks (friends, neighbours and relatives) are used to share and interpret the message, increasing the understanding of the contents, aiding in the informed decision making. A survey conducted by the United States 'Centers for Disease Control' (Sorensen 1992) found that about 40% of the respondents to the survey received emergency message from informal channels – friend or relative, either in person, or through telephone. Another study conducted by Sorensen (2000) specified that informal notification among the public plays an important role in warning dissemination in most emergencies. A tsunami warning study in Mauritius showed that about 15.4% public received face-to-face warning (Perry 2007). In this study, the significance of face-to-face communication was third behind TV and radio.

Another study (Werrity et al. 2007) reported the results of questionnaire survey among the residents of a Scottish flood plain region to understand the social impact of flooding. The study found that, among the surveyed households, 32% received the warning message from neighbours and about 51% of the flooded households actually received the message from official channels. The empirical evidence shows the significance of informal communication channel, and also the possibility (about 49% in this case) of some residents not receiving timely information from official sources.

A post-disaster survey after 2011 tsunami in Japan from 870 evacuees found that two main reasons for evacuation were strong ground motion (48%), and advice given by family members (20%) and neighbours (15%) (Mas et al. 2012a, p42).This highlights the role of unofficial channels in household evacuation decision and particularly neighbours.

Official messages that inform the public often request recipients to relay the message to neighbours and friends (e.g. Red-Cross 2005). For example Red Cross in Caribbean region had 'Run to thy neighbour' campaign as a means for increasing warning coverage. The role of young people and children as potential informants within emergency communication network is highly underestimated (Mitchell et al. 2008) and not directly accounted in the theoretical models of risk communication. This study (Mitchell et al. 2008) investigated the community initiatives in El Salvador and New Orleans, and demonstrated the possibility of using young people and children as trusted informants. They were imparted training in school clubs, and found to posses high understanding of local risk, communicate warning message and even state the actions for reducing risks.

In order to use the public as informants of warning message, it is essential to understand their behaviour during emergencies. There are widespread misconceptions that the public panic on receiving warning message (Fritz and Williams 1957, Quarantelli 1990), behave as victims, are highly dependent on officials resources and are helpless (Fritz and Williams 1957, Dynes 1990). There are various studies refuting such views, which also caution for developing emergency plans with these assumptions (Fritz and Williams 1957, Dynes 1990, Quarantelli 1990, Sorensen 2000, Maxwell 2003).

Mphunga community members in the republic of Malawi use community-based flood alerting system initiated with the help of Red Cross as a part of climate change adaptation strategies. Some community members were identified as 'Action team' who alert the public using whistles about the imminent flood (IFRC 2009b). They have identified a church that is at a higher elevation as a neighbourhood sheltering point. This is an example for planned/co-ordinated unofficial warning system.

The questionnaire survey conducted by Werrity et al. (2007) also investigated the local authorities for their warning and informing plans to various groups (p133) namely householders, landowners, and businesses ('Do you have systems in place to warn householders, landowners, businesses, directly? If so, how do they work?'). Apart from these groups, tourists, commuters, people living in temporary sites (e.g. caravans) and socially isolated are vulnerable (referred to as 'residual risk' groups in Werrity et al. (2007) and Handmer (2001), as they are less likely to be reached by the official warning channels and need to be included in the evacuation warning dissemination plan.

Table 2.7 Proportion of people who received a flood warning from an unofficial source (Parker and Handmer, 1998, p52 and p55)

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Apart from relatives and friends, the role of neighbour is significant owing to their physical proximity (Parker and Handmer 1998). A survey by Tunstall (1992 as cited in Parker and Handmer 1998) after the 1990 Maidenhead (UK) floods indicated that over 40% of the people who informally detected the flood warned their neighbours – this was slightly lower (37%) for other local regions (Parker and Handmer 1998, p55). Another survey indicated that 22% of respondents warned their neighbours (Parker et al. 2009). An example of spontaneous and voluntary dissemination of the warning message by neighbours was a midnight sub-urban fire where approximately 300 London residents safely self-evacuated themselves (Randhawa and Lydall 2009).

The primary warning was residents calling on their neighbours to confirm, personalise and interpret the warning message (Drabek, 1999). It is important to note in uncoordinated systems that not all people may warn the same number of neighbours, and the pattern of 'selection set' (choosing which neighbours to warn, e.g. adjacent and/or opposite houses) could vary due to prior contacts with neighbours.

Not all the families or individuals respond in the same way during emergencies (Kreps, 1984), which leads to uncertainty in the behaviour of the public as potential informants. Moreover, as each individual takes different time period to assimilate (receive, understand and react) the warning message, there is a possibility of longer time taken for disseminating to public when solely relied on informal communication (McLuckie 1970). The 'evacuation preparation time' is the time between the evacuation decision and its enactment (Hui et al. 2008). Warning response will depend on these different timelines and the understanding of the uncertainties of these times is required for the GOs to know time the onset of warning dissemination as well as overall warning dissemination time. The reliability of a warning system is likely to be increased when there are multiple channels of communication, rather than relying on a single channel. These studies support the observation of rational and active community behaviour, and also that the public could be potential informants for disseminating the emergency message. The behaviour of the public as informal channel needs to be modelled along with the official channels.

A report titled 'Developing early warning system – s checklist' contains useful information for the practitioners along with checklists for designing warning systems (UNISDR 2006a) and a comprehensive global review of EWS (UNISDR 2006b). An online forum called 'AWARE – Alert, Warnings and Response to Emergencies' (Botterell 2010) has provided a detailed summary on a standard for practice of public warning as various policy-level questions and this requires validation from real-life events. In order to measure the overall performance of warning systems, various studies (Stern and Sinuany-Stern 1989, Rogers and Sorensen 1991, Southworth 1991, Hui et al. 2008) have used 'overall warning level' (% people warned) and notification time (in minutes) as effectiveness measures. EMAs could use these performance metrics to compare various alternatives, set operational targets and plan for various scenarios to test the warning plan.

2.8.3 Modelling the evacuation warning dissemination process

Modelling warning dissemination would involve computing dissemination levels using effectiveness of official channels and also unofficial channels. Warning system effectiveness is defined as "*the ability of the warning system to provide population at risk with adequate time to respond appropriately to the situation*" (Rogers and Sorensen 1991, p129). Coverage is the maximum penetration that can be achieved using a particular warning channel within a specified time. Individual channel effectiveness will affect the overall system effectiveness. The ‘effectiveness of warning channels and its impact on overall warning dissemination’ has been modelled using two different approaches in the past two decades.

‘A macro-simulation’ looks at the aggregate level by dividing the city into different localities (not individual households) to model the overall warning dissemination. The activities of the household (e.g. travelling, in home and sleeping) and its impact on overall warning dissemination, were studied (Stern and Sinuany-Stern 1989) using a behavioural simulation model. Another study has validated the simulation model results with the empirical data of warning system effectiveness (Rogers and Sorensen 1991). Here the diffusion of warning message was depicted as logistic equation. But parameters in the differential equation need to be validated prior to the generalisation of these results.

Rogers and Sorensen (1991) took an OR approach to the modelling of the informal warning channel as ‘Contagion birth process’ using a logistic form of mathematical equation to model the official warning channel process. Even though the logistic parameters in their model were verified with a few empirical cases, their model does not capture the range of choices that households have (this thesis refers as ‘set selection’), for example whether households decide to warn a range of neighbours or not. Southworth (1991) used exponential form for the initial alert process and logistic form for the contagion process in the Regional Evacuation Model.

Second, ‘micro-simulation approach’ is where the individual entity (house) behaviour and its interaction with other entities (houses) are considered as the basic principle of modelling (see Gilbert 2007 for more details). As the interactions among the evacuees become the key feature of this approach, ABM is a suitable technique for this. Hui et al. (2008) used an ABM approach to model the diffusion of warning message among two hypothetical communities as a function of trust. This study used axioms to model the behaviour of the individual households and study the overall warning effectiveness.

These models (Stern and Sinuany-Stern 1989, Rogers and Sorensen 1991, Southworth 1991, Hui et al. 2008) use two KPIs for the warning process, namely ‘warning level’ (percent of population warned) and ‘notification time’ (time from the onset of the disaster to notify the population). The output of these models is depicted as warning response curves which is a plot showing the percentage of warned evacuees for various time duration.

A post-disaster study using Buoys, run-up heights, eye witness accounts and stopped wall clocks were used to obtain tsunami arrival characteristics after 2011 Great East Japan tsunami (Muhari et al. 2012). Tsunami wave arrival time for Fukushima to Aomori prefecture was found to be in the range of 25 to 55 minutes except in the case of Sendai region (which had higher values). This data indicates that from the epicentre of earthquake the time needed for the Tsunami wave to strike this region is between 25 and 55, and this time window is the time available for evacuation (from onset of warning to safety). Beyond this window, the tsunami wave would have struck these areas risking lives of non-evacuees and evacuating population.

As a planning estimate, utmost 30 minutes advance warning (notification time available) from the trigger of tsunami waves was used in Padang Indonesia (Taubenbock et al. 2009, p1521). However, the simulation experiments from MATsim model of Padang with inundation details showed that "*only after 40 minutes the entire population was evacuated*" (Taubenbock et al. 2009, p1525). This highlights that within the advance warning may not be sufficient for every household to be safely evacuated for the Tsunami scenario studied.

Micro-approach is data intensive as it requires information about the individual household details as well as warning channels. The warning channel and its effectiveness being a function of 'time of the day, availability of the channel as well the connectedness to the evacuees', can be modelled to answer policy-level questions like 'how long does it take to warn the public?' (Stern and Sinuany-Stern 1991, Hui et al. 2008). On the other hand a macro-level simulation uses aggregate data (e.g. for zone level TV viewership details) for answering the same policy-level question. The output of these approaches would depend on the accuracy of the input parameters and validity of the model.

One of the policy evaluation questions for warning dissemination is about "*Will special arrangements be needed for night time warnings*?" (Alexander 2009, p148). Households are mostly asleep during night-time and may not be connected to the main official channels (TV, radios) which are generally less effective in coverage at night. This highlights the need for evaluating warning dissemination for different time of the day and especially night-time conditions.

As there have been empirical evidences (Table 2.7) in the role of unofficial warning channels, there is a need for the EMAs to know how these unofficial channels will influence the overall dissemination. Though there was a simulation model developed for two hypothetical communities (Hui et.al 2008), there remains a research gap of exploring the use of agent-based-modelling for large-scale evacuations combining official warning channels and unofficial warning channels. Apart from this evacuation model, the suitability of agent-based modelling as technique for evacuation modelling has been increasingly recognised (Cabinet Office 2009) and also been applied in various social-simulation problems namely epidemiological studies, pandemic flu spread modelling, and rumour propagation problems (North and Macal 2007). This requires further investigation in studying how an integrated warning plan is prepared and the scope of using models to support EMA warning preparedness.

2.8.4 Research gaps on warning dissemination

The literature that informs ESF-1 includes the warning dissemination process, warning channel system and the scope of modelling the warning dissemination. The following are key research gaps identified in this thesis.

- The design of the warning message content was found to be well-established underpinning the social science literature (Sorensen and Mileti 1987) and the GOs could use this knowledge to design and test the sufficiency of content as one of preparedness initiatives. The review has highlighted the uncertainty of individual official warning channels in alerting the public as this could be studied using identified scenarios of failure.
- Even though there are tools like CAP-ONEs and strobe light (Sorensen 2000, Malizia et al. 2009) to warn vulnerable people during evacuation, specific ways of increasing warning dissemination to vulnerable people (visual and hearing impaired, houses with elderly people living alone) requires further investigation and are considered to be beyond the scope of this thesis.
- Modelling warning dissemination will involve aggregation of official channel effectiveness and unofficial channel effectiveness. The role of informal channel has been highlighted in Parker and Handmer (1998) and corroborates with empirical evidence (Table 2.7). Hui et al. (2008) studied using ABM the informal warning dissemination between two hypothetical communities and not at a city scale. The

dynamics of household choices as warning informants particularly 'their choice to be informant or otherwise' and 'selection of neighbours to inform' requires further investigation.

- The evidence demonstrates the importance of unofficial warning channel, and the EMAs need to formally exploit this 'unofficial channel' during emergencies. The delay in warning dissemination may have a cascading effect on evacuating to a safer place – and so it is closely linked to the analysis of 'When/how do they evacuate to safety' (ESF-2, Chapter 5) and 'where do they evacuate to?' (ESF-3, Chapter 6).

2.9 **Evacuee Transport Management – ESF-2**

Evacuee transportation model looks at the physical relocation of people from the hazard zone to the place of safety. There are various factors that would affect safe evacuation such as "*time available before (or after) the hazard impact, the expected travel demand, and the consequence of not clearing the area in a timely manner*" (Cova and Johnson 2003, p580). The authorities need an understanding about these factors to manage the traffic within the existing road infrastructure. The literature can be reviewed on two broad dimensions of Evacuee transport management. First is the household's transport choices and behaviour, discussed in Section 2.3.1 to 2.3.3. Second is EMAs transport infrastructure management, presented in Section 2.3.5.

After receiving the warning and complying with evacuation order, ESF2 covers the timeline from preparing to leave the household, departure, travel to safety. Evacuation time (ET) is defined as "*the time it takes for a person to start evacuating and get to a safe destination".* *(*Margulis et al. 2006). 'Evacuation time estimates' (ETE) have been widely as a means of measuring the effectiveness of evacuation used (Southworth 1991, Rathi and Solanki 1993, Lindell 2002, Han et al. 2007, Lindell 2008). Various key definitions on evacuation timelines were presented in section 2.1.1. The ET for a household is also referred using the terms such as 'clearance time or response time or travel time'.

Total evacuation time begins from the issuance of warning to the time a household reaches safety. There are various factors that affect when the evacuees receive the warning message and this is presented in Section 2.2. By preparing the public in advance (ERGO Model 1), having a household evacuation plan and providing them with supporting information during the evacuation, the preparation time can be reduced to facilitate the onset of relocating to the place of safety. Households first decide ‘whether they will evacuate or not?’ (or compliance to the evacuation order).

During Hurricane Floyd about 65% of the residents in the mandatory evacuation zone evacuated to a safe location (Dow and Cutter 2002, p13). A post-evacuation survey indicated that among the 73% of people who heard the warning order about 38% evacuated during Hurricane Katrina (Brodie et al. 2006, Table 2). During Hurricane Katrina the same study found that, among the non-evacuees who heard the message, 34% indicated that the reason for not evacuating is due to the ‘lack of cars’, 28% underestimated the storm and 12% could not leave the house as they were “*physically unable to leave or having to care for someone who was physically unable to leave as the main reason they stayed behind”* (Brodie et al. 2006, p5). This illustrates the various reasons for ‘non-compliance’ to the evacuation order apart from not hearing the warning message. On ‘deciding to evacuate’ a household makes three travel choices (departure time, destination and means of transport) and the literature review is presented in these headings.

2.9.1 Departure time

Given that the warning time will vary across households (as explained in Section 2.2), not every evacuee will be able to leave at the same time. During evacuation, the household members could be in different location depending on their activity (Roger and Sorensen, 1991) and this could have an impact on the departure time. The behaviour at the household level would impact on ‘when they will begin to evacuate’ as well as on their choices about their place of safety and means of evacuation. Transport planners in South Carolina have assumed three categories of evacuee departure response as a planning basis. Figure 2.3 indicates the response curves for rapid, medium and long response (South-Carolina, 2010).

Figure 2.3 Behaviour response curve reproduced from South-Carolina (2010)

Based on meta-analyses (Sorensen, 1991) of various rapid-onset evacuations like hazardous material accidents, flash flood and volcanic eruptions, the data showed that warning receipt and evacuation mobilisation times followed a logistic distribution (S shaped curve). The same study also summarised empirical evidences on departure time as presented in
Table 2.8.

Table 2.8 Summary of empirical evidence on departure time (based on Sorensen, 1991)

Evacuation incident	**Details about departure time**
Mississauga train accident	90% of first group <= 60 minutes. Including 60% <= 10 minutes
Confluence PA, Hazardous material release	85% evacuees <= 30 minutes on receiving warning.

A post-disaster joint survey with 870 evacuees after the 2011 Tsunami in Japan was conducted by Japanese Meteorological Agency, the Fire and Disaster Management Agency and the cabinet office. It was found that 57% evacuated immediately and 37% delayed their evacuation (Mas et al. 2012a, p42). Table 2.9 summarises the mobilisation time after being warned from the joint survey (as above) and another survey conducted in two cities (Kamaishi and Natori). For the Tsunami waves propagate from epicentre to the land there is time delay.

The ground motion (natural warning) and official warnings influence evacuees to depart as indicated in Table 2.9.

Table 2.9 Mobilisation time from post-disaster surveys (summarised from Mas et al. 2012a, p42)

Post-disaster survey	**Participants**	**Mobilisation time**
Joint Survey	870 evacuees	57% evacuated immediately.
Kamaishi city	113 evacuees	60% evacuated in less than 10 minutes
Natori city	107 evacuees	30% between 20 and 30 minutes.

A prototype ABM for Bush fire evacuation was developed, incorporating household behaviour in MATSim modelling platform (Padgham et al. 2011, p7). The following are some of the scenario and assumptions about the household behaviour reported for the model:

- Warning: A bush fire ignites at 1500 and at 1810 it is communicated to the impacted households. This is interpreted in this thesis as 70 minutes of notification time.
- Departure-time: Onset at 1500 + delay time (normal distribution with mean = 30 minutes and standard deviation 10 minutes).
- Destination: It is assumed that one-third of them would move to second local address.
- Evacuation response: All houses move to secondary local address or evacuation location identified by the authorities.

In order to model the household's departure time (i.e. warning + mobilisation time), based on exiting literature there are four main approaches as summarised in Mas et al. (2012a, p44):

i) Simultaneous departure – All the households leave together in 0 to 5 minutes after warning.
ii) Survey-based area-wise departure – A questionnaire survey results from the area are used for setting departure time for that area.
iii) Using evacuee psychology - Based on questionnaires with evacuees considering individual's psychological response to disaster and rational behaviour response.
iv) Behavioural response curves - Sigmoid curves fitted to the historical evacuation data or theoretical Rayleigh distribution.

These ‘departure time behaviours’ indicate varied responses from evacuating immediately or after a mobilisation time. The following section presents the second household travel behaviour namely ‘choice of destination’.

2.9.2 Choice of the evacuee destination

There are two major destination groups namely ‘public shelters’ and ‘private destination’. The factors that affect sheltering are explained in Section 2.4. From the point of view of transport planners, any destination will act as a sink towards which the traffic moves. When households leave to a destination outside the evacuated area (e.g. to a neighbouring city), transport planners will identify these locations to major exit points along the evacuation route. In the literature the choice of ‘private destination’ is influenced by various factors and classified into four groups (Southworth 1991, p25) as follows:

- Closest exit points based on travel distance or expected travel time
- Personal choice (location of friends and relatives)
- As per evacuation plan
- Existing traffic conditions

Evacuating to safety would involve relocation of the household members from the hazard zone to place of safety. This information of ‘destination choice’ is essential for the GOs to understand the flow of traffic during evacuation as well as providing sheltering support (elaborated further in the next section). The authorities in South Carolina, which is prone to Hurricanes conducted a stated-preference survey to know the destination choice of the evacuees. Table 2.10 indicates the choice of destination among the evacuating households (South-Carolina 2010).

Table 2.10 Survey from South Carolina (2010) on evacuation destination choice

Table 2.11 demonstrates the planning assumption about the destination of the evacuating public during hurricane evacuation. As the evacuees leave the house towards safety, there may be a need for them to change their destination for various reasons. A post-evacuation survey after Hurricane Opal (1995) was conducted to know the reasons for changing the destination, and it was found that over half of the evacuated public changed due to traffic congestions.

Table 2.11 Reasons for changing destination during hurricane Opal (NorthWestFlorida, 2010, Table 4.28)

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The choice of route and destination goes together. Four route choice selections have been presented for the evacuating vehicles (Southworth 1991, p29) to be incorporated in the transportation model. They are as follows:

- Myopic route selection behaviour, dictated by traffic conditions at each intersection
- System optimal or user optimal route selection behaviour.
- Combined myopic plus user route preference behaviour.
- Route according to an established evacuation plan.

2.9.3 Means of transportation and estimation of traffic volume

From the current hazard zone to the evacuation destination (place of safety), the evacuees will leave to safety through various means. When there are safe places within the neighbourhood of the evacuated zone, the evacuees could leave as ‘pedestrians’ and in other cases evacuees use vehicles (cars and public transport) for evacuation. A post-evacuation survey after Hurricane Opal (1995) indicated that about 62-68% of the vehicles registered in that area were used for evacuation with 1.16 to 1.36 vehicles per household (NorthwestFlorida, 2010). In another study, a stated-preference survey found that about 20% of the evacuees would require assistance for evacuation and ‘need transportation or the person had a disability or medical problem’ (NYC 2005). A questionnaire survey was used to obtain stated preference from evacuees for the case of tsunami evacuation in Japan (Suzuki and Imamura 2005). A multi-agent simulation of Arahama village (Mas et al. 2012a) used 72% evacuating with cars and the occupancy level as 4 evacuees per car.

In order to obtain the traffic volume on major roads, the authorities have used the O-D (origin and destination) studies as well as the ‘annual daily traffic data’. Apart from the vehicle traffic, the census data have been used to estimate the proportion of people at different zones (work zones, school and university and residential) in the city. For example, during the daytime, US census indicated (Southworth 1991) that 46.2% of population will be at work, 18.2% in school or day care and 35.6% as population will be at home. Though these values are geography specific, such an estimate could be collected by the GOs in their respective countries to support the transport plans.

In order to obtain a planning estimate for the ‘number of vehicles’, the authorities have used stated-preference surveys (FEMA 2010), and in another study (Southworth 1991), the number of registered vehicles in the area and number of licensed car drivers was used to obtain a planning estimate for number of cars. This estimate is essential to understand the expected vehicle loading at different zones during the evacuation. Finally, to obtain the number of evacuees safely evacuated, it is also essential to know the average number of evacuees per car and also how many vehicles per household.

As receiving the warning message on official channels (TV, radio, etc) would depend on the “time of the day” (Roger and Sorensen, 1991, p125), there will be a difference in the warning levels for a daytime scenario versus night-time scenario. Apart from this difference, the potential evacuees will be involved in different activities during different time of the day namely at work, sleeping, in transit and awake at home (Roger and Sorensen 1991). Based on the time of the day, the number of evacuees per vehicle was used as 1.85 daytime evacuees per vehicle (Southworth 1991, p13) and another study used 2.5 evacuees per car as an average value (Wolshon 2006, p6).

Apart from the traffic volume of the ‘resident population’, commuters and tourists form a major portion of additional evacuees. The proportion of commuter traffic could be obtained from ‘travel survey data’ (Southworth 1991). The percentage of tourists is specific to geography and GOs have used secondary sources (tourist department) to obtain an estimate of tourists in the city for a given season (FEMA 2010).

A two-stage linear programming approach was proposed (Murray-Tuite and Mahmassani 2005) considering the ‘household travel pattern’ in order to obtain a prediction of TET. Drabek (1996) discusses tourist and transient evacuee behaviour. Table 2.12 summarises the percentage of tourist in the city that has helped EMAs to support their evacuation plans. Finally, there will be additional ‘transient vehicular traffic’ along the evacuation route due to regular motorway users. This transient traffic could be estimated by analysing the historic volume of traffic along the evacuating routes and identifying a means of re-routing during evacuation to make more road capacity available for evacuees. Southworth (1991, p7) provides detailed calculation of traffic loading values.

Table 2.12 Average tourists (%) in different state zones (FEMA 2010)

For households evacuating as pedestrians and using cars, Mas et al. (2012a) represented speed variability using one-tailed normal distribution with maximum speeds as 1.33 m/s and 8.33 m/s (30km/h). This MAS model for studying 2011 Tsunami evacuation represented individual evacuees as agents with visibility cone of 60 degrees for both and visibility distance of 5m and 1m respectively for pedestrians and cars.

One of the major findings after Hurricane Katrina revealed that about 112,000 people, who did not have personal vehicles and were socio-economically poor population, were not evacuated. As the EMAs resources are over-stretched, the report advocated for "*neighbour helping neighbour policies*" (Wolfson 2006, p32). The report suggested that the poor people, who are generally more vulnerable during emergencies, "could arrange transportation with friends, family, neighbours and church members" (Wolfson 2006, p33). Apart from using community members as resource in the warning phase (Parker and Handmer 1998, Red Cross 2005, Mitchell et al. 2008, IFRC 2009b, Randhawa and Lydall 2009), this is another example of encouraging altruism among the evacuating households within communities.

2.9.4 KPIs for evacuation transport management

Measuring traffic flow and regulating the flow to best utilize the road infrastructure capacity is a wide field with significant body of literature. 'Highway Capacity Manual' is guideline for managing transport facilities published by Transport Research Board of US. Similarly, transport planners from various countries have identified and adopted traffic measurement systems to suit their infrastructure informed with research. 'Continuous Traffic Assignment Model' (CONTRAM) is a widely used across Europe for transport planning on non-emergency days. The interest of this thesis is to model the transport performance in the context of evacuation.

With the advent and wide-spread use of vehicle tracking mechanisms and ITS (intelligent transport systems), planners can choose to invest in sophistication at a needed level for managing traffic during the normal days. The role of monitoring systems during evacuation for decision support is contingent upon the existing operation systems used by the transport authorities. However, the level of transport preparedness is in the strategies pre-planned by the authorities on using the existing monitoring system. Preparedness also includes evaluation of transport performance for the planned evacuation scenarios. Simulation models have been used to model traffic flow by collecting 'measures of effectiveness'. For example, refer to Table 10.1 of Liebermann and Rathi (1992).

These KPIs help in assessing the transport management as an estimate of dynamic interaction of factors namely evacuation routes, household behaviour and transport policy. The household transport behavioural choices are complex and have influence on the traffic assignment (timing and volume) during evacuation. Chen et al. (2012) emphasised that evacuation risk is a function of pre-disaster factors and post-disaster events. Transport planners monitor traffic flow volume and monitor bottlenecks in the system during non-emergency days. This knowledge has a potential to be factored into evacuation planning. For example, an identified bottleneck could be a busy road junction or a road network that limits a quicker traffic flow rate.

During evacuation when the road infrastructure is stretched, the volume of vehicles is quite high and the bottlenecks could prove to be vulnerable as well. ‘Evacuation transport models’ in the hands of experienced transport planners (with rich observational experience on the road infrastructure) can be a vital tool for strengthening evacuation preparedness. Models have a potential to study these bottlenecks under evacuation condition for various transport policies in planned evacuation scenarios. Table 2.13 presents various indicators among different KPI categories.

Table 2.13 Various KPI categories for ESF-2 and corresponding indicators

KPI category	**Measures**
Overall evacuation performance	Departure time, travel time, total evacuation time. evacuation response curves for various means of transport choice
Network capability	Evacuation load distribution in various junctions, bottlenecks, traffic signals, key traffic entities (sinks)
Resource Utilisation	Public transport usage, occupancy, waiting times, etc

What measures are used to represent traffic flow? (Lansdowne 2006, p6)

1. Flow rate in a road section – Number of vehicles crossing an intersection per unit of time (vehicles per hour)
2. Traffic density – Number of vehicles per unit length of a road lane (vehicles per km of road)
3. O-D studies – Represents the origin (O) of vehicles to the destination (D) in order to obtain overall movement of traffic in a large network of roads. O-D is represented as matrix of size O x D.

One of the KPI is traffic flow rate and the data obtained during Hurricane Katrina are presented in Figure 2.4. During Hurricane Katrina, it was found that about 430,000 outbound vehicles were on major expressways, during the 48-hour period of evacuation (Wolshon 2006). With the advent of real-time traffic monitoring and counting systems that collect the vehicle details (including vehicle registration) through junctions, it is possible for the authorities to obtain an estimate of the 'number of departed houses' as the evacuation is ongoing. EMAs by measuring these KPIs for their road network will provide empirical basis for managing transportation during evacuation.

Figure 2.4 Traffic flow volume in a major road segment during Hurricane Katrina (Wolshon 2006, Figure 4, p32)

2.9.5 Supporting evacuation through transport management

Transport infrastructure is generally planned/designed for normal traffic conditions and not for evacuation-level demand (i.e. evacuation of entire city/regions in a short time period) (Wolshon 2006, p28). This would entail transport authorities to evaluate the capacities of infrastructure (road network, public transport capacity, manpower, etc) under planned evacuation scenarios as a foundation for evacuation preparedness.

A transport plan is a compendium of choices decided by the authorities on various transport infrastructures. For a transport response plan, the household evacuation choices (micro-behaviour) can have considerable influence on the overall evacuation success (macro-behaviour). Apart from the knowledge through personal experience, there is no other means of gaining confidence on transport plans with 'evidence base' at the preparedness stage. The transport models can be helpful in studying the uncertainties in household choices and to choose relatively better transport option by measuring the overall evacuation KPIs.

There are various means of supporting the evacuation by the transport officials in reducing the evacuation time, such as providing public transport (Schwartz and Litman 2008), regulating traffic flow through contra-flow plans (Kim et al. 2008), regulating traffic signal timings and providing routing plans to the evacuees. A technical report's recommendation prepared by the GOs in the New York City indicated that *'if officials aggressively urge evacuees to use public transportation rather than their own vehicles, approximately half the evacuees will comply, further reducing the number of vehicles used in the evacuation'* (NYC, 2005).

As the number of evacuees per vehicle in a public transport (say bus or metro) is high, leading to lower number of vehicles on roads, this demonstrates a means of reducing traffic volume during evacuation. Apart from the resident population, tourists are vulnerable with respect to transportation and would rely on the public transport. For this, the GOs need an understanding about the transport resource capacity (number of buses), trip scheduling and capacity of the road networks.

Public transport during evacuation

A bus dispatch system was proposed to schedule the bus services for facilitating the evacuation (Margulis et al. 2006). The following were the operational and behavioural assumptions made while developing the system.

1) The time it takes to go from a pick-up point to a shelter is fixed.
2) There is a maximum amount of trips that a bus can make.
3) Refuel delays are negligible or taken into account in the loading/unloading variable.
4) People will go to the closest pick-up point.
5) All bus demand is concentrated at the pick-up points.
6) Demand at the pick-up points is present from the start of the model timeframe.

Though the study has stated the underlying assumptions of the model, this requires validation of the transport organisational practices as well as the behaviour of the public as intended/assumed. For example, the authorities making assumption on the pick-up point (No. 4) need to have identified the bus stop locations designated as pick-up points and, importantly, to have communicated this information at the preparedness stage (e.g. through leaflets) as well as during the evacuation (e.g. media reports).

Streamlining evacuation traffic using signals

Modelling traffic signals using OR/MS methods is at least four decades old (Little 1966). During no-notice evacuation, vehicles leave in a short time window and hence the signal timing becomes critical. A simulation study to test signal policies found that '*the longer the cycle length used, the better the performance in terms of the number of vehicles to escape in a given time period, but the worse the performance in terms of delay to vehicles on the minor roadways.*' (Chen et al. 2007). The performance measures namely maximising throughput (number of vehicles cleared) and 'maintaining fairness in delays along major and minor roads' were used to test the signal policies. For the existing road network and the estimated traffic flow, EMAs could test their signal system and identify a suitable 'timing' strategy to facilitate evacuation.

For example, VISSIM is a micro-simulation multi-modal tool used for managing signals using prioritised policies for buses (Fellendorf 1994). An optimal phase length (green duration) was arrived at using the model by considering traffic flow conditions and the network design. ABM traffic simulation model was used to study the impact of different traffic signal plans on average delay time of vehicles (Jamshidnejad and Mahjoob 2011).

Vehicle agents' movement in a traffic system were studied with different green signal duration (25, 50, 75 and 100 seconds) on successive intersections in a synchronized manner. Signal groups along a particular road are synchronised such that the vehicles have lower likelihood of being stopped in 'successive' signals by using field observations from drivers (Shinar et al. 2004). In another study a 'Mixed-integer programming problem' was formulated and solved for obtaining phase length for urban signal groups (Little, 1966). Transport and Road Research Laboratory (TRRL) of the UK have developed SCOOT method for real-time optimization of signals in five cities (Robertson and Bretherton, 1991). As the volume of traffic is expected to be very high during evacuation, the role of signals when managed well can streamline the evacuating traffic and reduce congestion. For more information on signal controls, readers are referred to Lammer and Helbing (2010), Lin et al. (2009), and Mu et al. (2011).

Regulating routes to increase evacuation network capacity

'Contra-flow plan' is a means of increasing the traffic flow capacity on a multi-directional road network, by altering the direction of traffic flows in the same direction to facilitate evacuation. Contra-flow plans are designed considering the expected traffic flows and existing road networks (Shekhar and Kim, 2006), and this is widely used in the United States. Based on the characteristics of Hurricane Ivan, a simulation model indicated that, compared with a plan without contra flow (the "do-nothing" alternative), the proposed plan of contra-flow would nearly double the amount of evacuating traffic over this same period. Table 2.14 based on Wolshon (2006) indicates that the contra flow plan is a very good response option for reducing the TET.

Table 2.14 Performance of Contra-flow plan to reduce evacuation time (Wolshon 2006)

Apart from contra-flow plans, there has been extensive studies on obtaining evacuation routes for different zones of a city by using 'multi-objective evacuation routing' (Stepanov and Smith 2009) and ABM (Chen et al. 2006). Another simulation study combined DES and GIS (Geographical Information System) to identify congestion management strategies (Wiley and Keyser 1998). Apart from the existing evacuation traffic performance metrics namely average traffic flow rate, average speed, link travel cost and TET, this study has proposed new measures of performance (MOP): *'ratio of queuing vehicle to total vehicles on the link' and 'simulated travel time as percentage of free flow travel time'*. These metrics can be used by the GOs to devise transport response plans and measure their organisational preparedness. The evacuation routing information is either pre-designed or chosen during the response. This information will play a key role in influencing the behaviour of the evacuating public. For various traffic management strategies during major emergency situations refer to Wohlschlaeger and Ullman (1992)

2.9.6 Modelling of evacuee transportation process

Transportation models can be broadly classified into two categories, depending on the level of detail included in the model. First, 'macroscopic' models treat every vehicle as the same and do not consider individual vehicular behaviour and evacuation route choices. On the other hand, 'microscopic' traffic models consider the individual vehicle behaviour and model their interactions as well as changes (Hamacher and Tjandra 2002).

Generally optimization models are macroscopic transportation models widely used in the literature (Sherali et al. 1991, Hamacher and Tjandra 2002, Lindell et al. 2002, Barbarosoglu and Arda 2004, Kongsomsaksakul et al. 2005, Han et al. 2006, Johnston and Nee 2006, Stepanov and Smith 2009, Bretschneider and Kimms 2011). Any evacuation traffic simulation model need to have 'dynamic traffic assignment' (DTA) component that enables modelling the departure of vehicles (loading) into the road network and its navigation in the system. Readers are referred to Juran et al. (2009) and Ben-Akiva et al. (2012) for more information on DTA models. As evacuation is often a response to a disaster with many of transport choices made at the household level and also influenced by EMA evacuation plans, evacuation models are special extensions of traffic simulation models.

Santos and Aguirre (2004) reviewed the existing evacuation models and this thesis will adopt the same categories for grouping the models namely flow-based models, agent-based models, cellular automata-based models and activity-based models. Evacuation modelling of facilities has been used extensively to obtain evacuation plans. For example computer-based models have been used for football stadium evacuation modelling (Elliott and Smith, 1993), Haj Jammarh bridge (Crowd-Dynamics, 2010) and Kings Cross underground station evacuation (Castle, 2004). ABM has been extensively used to model pedestrian evacuation from the facilities (Kerridge et al. 2001).

For representing a major evacuation in a city, both the spatial information (different zones in the city) and the road network details need to be combined for developing a model. Computer models provide a means for testing the 'planning assumption', measuring the 'relative effectiveness' of various response strategies and identifying 'vulnerability' in the network. For example, the proportion of public transport usage was tested using a Linear Programming model (Margulis et al. 2006) for 10% and 25% to understand the response capability of bus, given the existing road infrastructure and number of buses (capacity). This will help the authorities to understand the implication of the assumption as well as to identify bottlenecks in the transport plan.

Evacuation strategies were classified as simultaneous (*all vehicles are evacuated concurrently*) and staged evacuation (*evacuation is done by prioritising different zones*) in order to reduce congestion and minimise the evacuation time. Chien and Korikanthimath (2007) proposed a numerical method approach to measure the relative effectiveness between simultaneous and staged evacuation and it was found that *'ET and delay can be significantly reduced if staged evacuation is appropriately implemented'*. The model was also used to find out the optimal number of staging required along with the priority sequence for a road network.

Another study by Chen and Zhan (2008) used an ABM for obtaining relative effectiveness among the two strategies, and it was found that "*staged evacuation is good where population density is high and road network structure is a grid structure"*. Murray-Tuite and Mahmassani (2005) proposed a game theory-based bi-level optimization problem to identify the vulnerable locations in the transport network by defining 'vulnerability index' for major roads. In terms of accessibility to highway system, a simulation model was developed to evaluate the significance of the road network links (Sohn, 2006) leading to reliability-based routing plans.

There is a wide range of computer-based models that have been used by transport authorities for planning evacuation.

A review of various modelling software are available in Pel et al. (2011, p168). Models provide a platform for testing response plans, training staff and exercising the preparedness strategies. For a review of transport policies and practices for hurricane evacuation refer to Wolshon (2006), Litman (2006) and Han et al. (2007). Though these studies have presented the findings for hurricane, the evacuation phases are applicable to other emergencies.

Table 2.15 provides a summary of the important models. A comparison of various transportation models such as OREMS, DYNEV, ETIS, VISSIM, DYNASMART-P and MITSIMLAB, is available in Qiao, Ge and Yu (2009, p8) S-Paramics is another micro simulation traffic flow modelling system that is widely used and the model for City of Almere evacuation has been presented in Tu et al. (2010).

A review of various modelling software are available in Pel et al. (2011, p168). Models provide a platform for testing response plans, training staff and exercising the preparedness strategies. For a review of transport policies and practices for hurricane evacuation refer to Wolshon (2006), Litman (2006) and Han et al. (2007). Though these studies have presented the findings for hurricane, the evacuation phases are applicable to other emergencies.

Table 2.15 Review of existing evacuation models

Model	**Reference**
REMS – Regional Evacuation Modelling	Tufecki and Kisko (1991)
OREMS – Oak ridge evacuation modelling system	Southworth 1991
FIRESCAP	Feinberg and Johnson 1995
EXODUS	Filippidis *et al.* 2003
MASCM - Multi-agent simulation for crisis management	Murakami *et al. 2002*
SIMULEX	Thompson and Marchant 1995
Kings Cross Underground station simulation	Castle 2004
PACKSIM	Barcello 1993
EMBLEM2	Lindell 2008

MATSim (Balmer et al. 2006) is another modelling platform for large-scale evacuation modelling. One of the applications of MATSim has been used to develop a prototype model evacuation due to fire in Breamlea, Australia by incorporating "*individual household/Vehicle evacuation decisions*" (Padgham et al. 2011). It is interesting to observe that for modelling evacuation process, an evacuation decision of household (agent) 'prior to evacuation' requires setting behavioural rules at the household level. Once they 'depart' using their chosen evacuation means/vehicles, the further phases of evacuation are transferred to a vehicle (agents) on the evacuation network. This bi-phased ABM (house – agent prior to departure, Vehicle – agent during transportation) is more suitable way of capturing different phases of evacuation and requires aggregation of evacuation behaviour in different agent units.

Car-following model provides an algorithm for deciding on car movement of a trailing car based on the leading car's stated. Based on the model configuration of leader-follower pair, level of details and the variables included, there are many car-following models available in the literature, and the readers are referred to Zheng, Suzuki and Fujita (2012), Ossen and Hoogendoorn (2011, p186), Helbing et al. (2002) Brackstone and McDonald (1999, p185), Gipps (1981) and Gazis et al. (1961) for more detailed information. The following are key car-following models.

1. The Gazis, Herman and Rothery (GHR) Model
2. The Chandler, Herman and Montroll (CHM) Model
3. Bexelius-modified CHM with two leaders
4. Tampere Model
5. Addison and Low model
6. Gipps Model
7. Intelligent Driver Model (IDM)
8. Optimal Velocity Model (OVM)
9. Lenz-modified CHM with two leaders.

Driving behaviour of different vehicles (cars and trucks) was studied using trajectory data obtained by means of helicopter (Ossen and Hoogendoorn 2011). This data was further used to compare different car-following models and also the heterogeneity in driving behaviours of cars and trucks. This study found that the speed data of truck drivers showed less variation over time compared to car drivers. Also the headway gap of a passenger car while following a truck was higher compared to that while following another car.

For the factors namely distance to the leading vehicle (headway) and speed, the range of difference values with the leading vehicle has been used and classified (Schulze and Fliess 1997). These limits were used to define the vehicle's state in a car-following model in successive iterations. The car-following logic using these two parameters has been used in Lansdowne (2006) and requires minimum data for the algorithm.

2.9.7 Research gaps on evacuee transportation management

Generally, in rapid-onset disasters, the evacuation window available is short (in order of hours) and the household time series of receiving warning dissemination is very critical. Depending on the official channel effectiveness and the level of unofficial channel, households receive warning at different points in time. Further, for a rapid-onset event (e.g. flooding), the need for having short preparation time is essential for onset of household evacuation (departure) and travelling to their chosen safe locations (shelters/exits). The household's evacuation travel time is influenced by their transport means, departure time, influence of transport policies and other evacuating vehicles. This highlights the need for multi-phased integrated approach for modelling evacuation, and it is argued in this thesis that for a realistic evacuation planning for 'planned scenarios', not incorporating warning dissemination phase in transportation models is treated as undesirable. As the departure time is a function of warning time and the existing models use departure curves (Mas et al. 2012a) that do not specifically model the warning dissemination, this thesis would study the impact of warning dissemination including unofficial channels on transportation KPIs.

As the volume of traffic during evacuation is very high due to simultaneous departures in a short window (Wolshon 2006), the role of existing traffic in the network, particularly transient traffic, will reduce the capacity available on evacuation routes. This thesis will study the impact of transient traffic on the evacuation times. The thesis will also identify from the existing literature various transport management measures available for the EMAs and illustrate how models can play a role in measure preparedness.

Evacuee transport studies restrict to pedestrian and vehicular (cars) means of transport (Clarke and Habib 2010, Mauro et al. 2013). However, public transport using evacuation bus plays a key role in evacuation (Margulis et al. 2006); given the findings from Hurricane Katrina that 'lack of transportation' was one of the reasons for evacuation, this thesis will investigate the scope of using transportation models to support bus dispatching operation. The next section presents the review of literature on public shelter management.

2.10 **Emergency accommodation planning: ESF-3**

Emergency accommodation, though the last phase in evacuation, is one of the important phases in the mass evacuation of a city, bridging the gap between evacuation and safe recovery/return. There are various terms used in the literature to denote emergency accommodation: sheltering, public shelters, mass care shelters, refugee centre, emergency accommodation and humanitarian assistance centre, and this thesis will refer to these as shelters.

Hurricane Katrina and Rita displaced about 2 million people and more than 250,000 were sheltered for more than two weeks (Burkle 2009). The duration of sheltering could be as short as few hours (e.g. evacuation for unexploded bombs of World War II) or it could be for months depending on the nature of the emergency, immediate effect on their houses and proactive measures taken by the public. For example, the duration of sheltering during Hurricane Andrew evacuation was five weeks (Sattler et al. 1995). Thus GOs responsible for shelter management need an understanding of sheltering as well as identifying, allocating and managing the shelter for a city.

2.10.1 Planning for sheltering

This section reviews emergency accommodation planning, and is grouped into the following sub-sections: classification of shelters, estimation of demand, sheltering availability and allocation, relief supplies planning and support services.

Classification of shelters

Sheltering involves relocating evacuees from a hazard zone to a place of safety. There are many alternatives to be evaluated prior to issuing an evacuation order. The alternatives are (Xu et al. 2006):

- In-sheltering (staying in a safe place within the premise),
- Vertical evacuation (moving to the floor above especially used in flash flooding) and,
- Horizontal evacuation (leaving the threatened location to safety).

The detailed analysis of the 'evacuation decision making' by GOs has been presented in Model 2 (Shaw et al. 2011a). Once the evacuation decision is made, the warning message will provide information about evacuating to shelters. Shelters are broadly classified (Kar and Hodgson 2008) into 'special facilities' (specifically built for emergency accommodation) and dual-use public buildings (schools, colleges, churches and community centres).

Depending on the relative location of the shelter from the evacuated zone, the shelters are classified into four categories based on 'spatial scales' (Xu et al. 2006, p183).

Table 2.16 lists these categories along with their features. Each category of sheltering level will have different needs depending on the duration of sheltering. For example, when the evacuees are relocated to a regional level shelter for long duration (say one week), there will be a need for lifeline support (e.g. food, bedding, medication, etc.) until safe to return.

The choice of sheltering level would also impact the transportation aspects, namely the means of transportation, vehicles per household, departure time and role of information about evacuation routes (Dow and Cutter 2002, p13). This highlights the inter-relatedness of the three ESFs (warning dissemination, transportation and shelter management). As the shelters are located in different parts of the city, the spatial distribution will have an impact on TET.

Table 2.16 Classification of shelters and its key feature.

Sheltering level	**Feature**
Household Level	Safe room within the house – for flooding, earthquake and some nuclear disasters (in-sheltering)
Neighbourhood level	Building in a higher elevation and safe – for fire and earthquakes - refugee point.
Community level	A shelter location identified in advance within the community (e.g. neighbourhood leisure centre).
Regional Level	When there is wide spread damage to the houses within the region, the evacuees are sheltered in the neighbouring region.

2.10.2 Shelter demand estimation

A city's population can be broadly classified as 'resident population' and 'transient population' (Johnston et al. 2007). Resident population comprise people who live in the city area. The transient population includes commuters, visitors and tourists. Not all the evacuees will comply with the evacuation order. For example, during Hurricane Floyd only about 65% evacuated from the danger zone (Dow and Cutter, 2002). Among the evacuated people, the proportion of people who will require sheltering will vary. The demand (defined as number of evacuees needing shelter) for public shelters was explained in Mileti et al. (1992) by various factors and grouped into three categories:

a) Characteristics of the disaster event.
b) Characteristic of the emergency preparedness.
c) Characteristics of the evacuees.

Table 2.17 Classification of factors that affect shelter demand (Mileti et al. 1992)

Table 2.17 summarises the findings from various published sources as presented in Mileti et al. (1992). Such a study could help GOs to understand the factors affecting the shelter demand. The 'Nanticoke metal fire evacuation' (1987) resulted in 15000 residents being evacuated including 250 hospital and nursing home patients (Stambaugh 1987), and shelter usage during this evacuation was about 43.2% (Duclos et al. 1989). The demand for shelters can be estimated based on the number of people exposed to the threat (Mileti et al. 1992). GOs can estimate these 'expected evacuation zones' using disaster-specific OR models (e.g. the flood model). Thus GOs could combine the demographic data of the area with the threat information (Ng et al. 2010) to determine the evacuation zone, which would in turn provide the number of evacuees. The synthesis of historical records detailing the 'usage of shelters' for different hazards is summarised in Mileti et al. (1992), but caution should be exercised in relation to the effect of other factors (e.g. severity of the disaster, socio-economic profile, etc.) on the generalisability of these observations. Table 1.1 can also be analysed to obtain hazard-specific estimates of sheltering as percent of population and sub-divided into disaster intensity.

The authorities responsible for shelters have used policy-level questions like, "*What are the destinations of the evacuees and what type shelter will they be heading for?*" (Alabama 2010). For the evacuees complying with the evacuation order, there are various alternative destinations. They are:

- Evacuating to public shelters.
- Staying with friends or relatives.
- Go to a hotel or motel.
- Go to church or workplace.

In order to obtain data for supporting their plans, the Alabama authorities (FEMA 2010) have used stated-preference surveys from the residents living in the community. The data was collected in each county in Opal and grouped into four shelter destinations (public shelter, friends/relatives, hotel, others). 'Staying with friends/relatives' was widely stated preference. The evacuee behaviour data helps in estimating the demand for public shelters during an evacuation.

The average demand for mass care shelters in United States was reported to be 15% (Sorensen 2000). Depending on the socio-economic profile of the evacuated zone, the demand will vary considerably in different zones (FEMA 2010). In order to understand the expected variation, the authorities have used post-evacuation surveys to create a planning estimate. Based on a post-evacuation survey conducted (Brodie et al. 2006) after the Hurricane Katrina evacuation, it was found that about 30% (8000 people) were sheltered out of the 27,100 resident population. This study also highlights the sheltering usage is influenced by 'ethnicity' (African-Americans were about 93% of Houston shelter residents), low income level, low rate of home ownership, health insurance, education level and marriage status.

These findings, even though specific to geography (Houston area, United States) and a disaster type (Hurricanes), highlight the factors that would possibly affect the evacuees needing shelters (shelter demand). EMAs as a part of preparedness initiative could arrive at a planning estimate of 'shelter demand' considering these factors. EMAs could also identify the sheltering locations and document its capacity (how many people who can be sheltered). For theoretical basis of shelter demands refer to Mileti et al. (1992).

Shelter availability estimation and allocation

Shelters are often pre-identified and documented as a part of preparedness initiative. The names and addresses of existing shelters can be geo-coded to produce an existing shelter geographic database (Kar and Hodgson 2008). The responsibility of 'identifying the potential sheltering locations and documenting them' is an important preparedness task (Cabinet Office 2006). For a large-scale evacuation, the database of shelters will be used to identify the available shelters, depending on the damage to shelter building by disaster, evacuation distance and life-line facilities available, etc.

Table 2.18 highlights a variety of dual-use buildings identified for potential use as shelters (Kar and Hodgson 2008). The capacity of these shelters (number of people who can be accommodated) will be varied comparably in the list given below. As the identified shelters will be dispersed across different regions in the city, the available shelters need to be allocated for different evacuation zones.

Kar and Hodgson (2008, p227) presented a GIS-based selection from the available location on the following policy level questions on 'shelter suitability':

1) *How many candidate shelters are located in physically suitable areas (e.g. not in a flood-prone area, not near hazardous facilities, etc.)?*

2) *How many existing shelters are located in physically unsuitable areas, but in socially suitable areas (situated in areas with demand)?*
3) *How many alternative existing and/or candidate shelters with high/very high physical suitability are located near physically unsuitable existing shelters and thus, may be better choices for a shelter?*
4) *How many existing shelters located in physically unsuitable areas are not near alternative existing and/or candidate shelters?*

Table 2.18 Facility type considered for sheltering (Kar and Hodgson 2008, p235)

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These suitability questions were used to obtain a ranking of candidate shelter locations and select the higher ranking ones for sheltering. Given that the shelters are identified in safer zones with different capacities, the evacuees from different zones need to reach different shelters. The GOs could allocate the shelters based on a priority.

In order to understand the distributiveness and coverage of the shelters, OR models have been used to choose optimal shelter location. Sherali et al. (1991) used a mathematical modelling approach to formulate a location-allocation problem to select the best shelter locations among available shelters by minimising congestion and TET. The sufficiency of the number of shelters and its coverage to various zones (Chiyoshi et al. 2003) of a city can be studied as a 'location search problem' (Brandeau and Chiu 1989) to help in identifying new shelters. For the case of flooding threat in Mozambique shelter planning was using GIS-based spatial analyses to identify shelter candidates outside the flood-prone areas with transportation route access to it from the living population (Gall 2004). Another study used GIS tool to do shelter site selection for Denton, Texas United States (Lea 2009). These OR models will help GOs to understand the coverage of shelters to different evacuated zones.

As the demand locations (evacuated zones) and supply points (shelter locations) are geographically spread out, the ET must be balanced such that the evacuees quickly reach to safety. This would entail understanding the behaviour of evacuees in evacuation route choice, travel time and speed and considering these while allocating the shelters. New Hannover County, which is prone to various disasters like flooding, wild fires, tornadoes and earthquakes, has publicised various evacuation shelters in their website using a map (NHC 2010; NHC-S 2010).

Mas et al. (2012a) used two alternatives for household's shelter choice namely 'closest shelter' and 'any random shelter'. The study also mentioned that "*in many cases the preference is not necessarily the nearest shelter*" but no empirical evidence was quoted. During the absence of any prior information about their allocated shelters, the evacuees might go to the nearest shelters or a convenient shelter. In some instances the evacuees were "*assigned particular neighbourhoods to them*" (Mileti et al. 1992, p33) and this will influence their 'travel choice behaviour' during the evacuation. Thus based on the literature, there are three choices available for households allocated shelters, nearest shelter, and any other shelter.

"*In many cases, not only the capacity of these shelters plays an important role, but the spatial distribution and the evacuee preference for the nearest shelter. Such preference and location creates conflict between capacity and demand.*" (Mas et al. 2012b, p61). A multi-agent-based simulation model for La Punta, Peru, modelled the pedestrians choosing nearest shelter from their residential zone and evacuate to it. It was found from 250 simulations that among 20 shelters, 13 (65%) had arrivals exceeding capacity and 7 (35%) were under-utilised. This overall capacity-demand mismatch was due to independent shelter preference of the household. The dynamics of the household preference for 'nearest shelter, convenient or random choice' and shelter capacity management needs further investigation.

The household's shelter choice also affect the household's travel time (or clearance time), traffic flow rate and other household's ET. GOs responsible for allocating the shelter would aim at minimising the TET (sum of the evacuation time of all the evacuees) and this approach is referred to as system-level optimization (cooperative behaviour). The GOs' decision could be divided into a 'location problem' (Sherali et al. 1991), with an objective of identifying zone-wise shelters. The evacuees choose their best shelter depending on the information available prior to the event (e.g. from leaflets), on instructions given in the warning message stating shelter location as well as on evacuation routes and personal preferences (e.g. evacuating to nearest shelters). Failure to undertake these actions could result in non-optimal behaviour, which "*could potentially lead to overcrowded shelters and/or severe traffic disruptions*" (Ng et al. 2010).

Kongsomsaksakul et al. (2005) proposed a bi-level 'Stackelberg game' by combining the GOs' perspective as well as evacuee behaviour choice. This problem was solved using 'Genetic Algorithm' which is a heuristic technique for solving optimization problems. A more recent approach for allocating shelters was using hybrid bi-level (Ng et al. 2010), which involves solving the optimal shelter allocation in two stages. First the problem was solved at the 'authorities' perspective' and then the next level was solved at each evacuation zone. In all these models the TET of all the evacuees was used as a performance metric which was minimised by balancing various constraints:

- Available shelters
- Shelter demands
- Evacuee behaviour
- Travel time from the hazard zone to the allocated shelters.

This section has explained how OR models have provided a means of understanding various aspects on shelter allocation. Shelters also require lifeline supplies and staff to deal with evacuees. Some of the key shelter operation services are 'managing evacuee registration process (CBC 2010, Chatham 2009), missing person information and hotline facilities (Mills et al. 2007), psycho-social support for handling post-traumatic stress disorder (PSTD) (Werrity et al. 2007) and managing the emergency logistics (Ozdamar et al. 2004)'. For detailed information on relief supplies to shelter and support services refer to Shaw et al. (2011a, p93).

2.10.3 Research gaps in emergency accommodation management

The previous section reviewed the literature on different aspects of 'emergency accommodation plans' namely understanding the factors influencing the demand and its estimation, identifying the shelters and allocating shelters during the evacuation and the shelter operations. The review also presented the application of analytical models for supporting the shelter allocation. The following are key research gaps identified from the literature:

- The level of household compliance to information in the context of evacuation has already been investigated (Pel et al. 2010). With respect to shelters, there are various preferences (Kongsomsaksakul et al. 2005, Mas et al. 2012b) such as nearest shelter, convenient shelter, allocated shelter, etc, which influence household's shelter choice behaviours. The relationship between 'household's shelter choice behaviours (which shelter they reach?) and its impact on the overall shelter arrivals need to be investigated further. Overseeing the management of capacities available in all shelters and its influence due to the household choice will be of interest to the lead EMA.
- Literature is available on individual tasks in sheltering management; however no generalisable approach that enlists all the tasks for the practitioners is available in literature.
- As the shelters are spatially dispersed across the city, how the EMA make optimal shelter allocation can inform other ESFs (like evacuation bus routes) and also influence the household's travel choice behaviour?

2.11 **A need for integrated evacuation planning**

A study after the 1995 Kobe earthquake argued that "*the response management in Kobe earthquake was non-optimal. Integration, coordination, communication and planning were insufficient to cope with large disasters*" (Heath 1995 as cited in Ventura et al. 2010). Even though this study is close to two decades old, it corroborates with 2005 Hurricane Katrina's findings (i.e. the need for coordinated multiagency response). The need for an integrated planning to large-scale evacuation is relevant even today. There is even more need to research on this topic, given the increase in complexity of recent disasters (e.g. the 2011 Earthquake-Tsunami-Nuclear disaster in Japan), making multi-agency-based evacuation planning a necessity. An evacuation response plan from 'warning to safety' involves three ESFs as identified in this thesis, with each ESF having many individual organisations collectively responding during evacuation. The inter-dependency and inter-relationships among these phases during evacuation in terms of 'evacuation time estimates' need to be studied in this thesis.

A tsunami risk reduction study using multi-agent simulation model of pedestrian and vehicular traffic was studied for the city of Padang, Indonesia (Mauro et al. 2013). The arrival time of tsunami is expected as approximately 30 minutes. It was found that "*the evacuation rate in the first 30 minutes is strongly dependent on the presence/absence of evacuation* *shelters, whose effectiveness is limited by the capacity of structures (referring to shelters)*" (Mauro et al. 2013, p1). This highlights the inter-relationship of ESF phases between tsunami arrival time, real-time shelter availability, household behaviour and ET.

The nature of relationship in the evacuation context is physical (one ESF follows the other), a household's state changes (from warned, evacuated to safe) and these impact KPIs of ESFs. Household's evacuation time (KPI) is additive value of 'warning time' (ESF-1's KPI), mobilisation time, departure time (ESF-2's KPI), evacuation travel time (ESF-2's KPI). *What is the direction of relationship among ESFs? Is there also information interdependency among the three ESFs?* These are some of the questions that require further investigation in this thesis in order to understand the need for multi agency-based integrated evacuation planning.

General findings on OR modelling for three ESFs

As the emergency response requires coordination between various organisations on different aspects of emergencies (e.g. hazard forecasting, warning, traffic management, etc), a tool based on integrated simulation approach will provide a platform for holistic view (Jain and McLean 2003). The success of disaster response is substantially affected by effective inter-organisational coordination among the emergency responders (Perry and Lindell 2003) and the OR models will facilitate different responding organisation to support their response planning using models as a test-bed.

For the case of tsunami threat in the city of Padang Indonesia, Taubenbock et al. (2009, p1509) developed an interdisciplinary approach for tsunami evacuation preparedness. Evacuation information system has components of "*inundation modelling, urban morphology analysis, population assessment, economic analysis of the population and a multi-agent based evacuation model*". It was found from the model experiment that "*only after 40 minutes almost the entire population was evacuated from potentially inundated areas from the sample tsunami scenario*"(Taubenbock et al. 2009, p1525).

A multi-agent simulation model was developed for a case study of coastal town called Towyn in the United Kingdom for flooding using risk-based incident management (Dawson et al. 2011). "*The multi-agent simulation has coupled with a hydrodynamic model to estimate the vulnerability of individuals to flooding under different strategies*" (Dawson et al. 2011, p167).

The model was "*used to evaluate the effectiveness of 'flood incident management' such as flood warning and location of shelters*" (Dawson et al. 2011, p186).

An integrated tsunami and evacuation simulation model (TUNAMI) was used in a post-disaster study after 2011 great eastern tsunami in Japan (Mas et al. 2012a). The model was developed for Arahama village in Miyagi prefecture in Japan with population of 2704 residents. This multi-agent simulation model had components on Tsunami wave inundation models, collision avoidance model for pedestrians and cars, and evacuation destination as identified tsunami evacuation buildings and two exits. This model however didn't use the warning data instead compared departure times using stated preference surveys and sigmoid curves.

An integrated tsunami inundation and evacuation model TUNAMI-EVAC1 (Mas et al. 2012b) was developed for La Punta, Peru with a population of 4370 in order to estimate the ET, casualties and impact of household behaviours. The model has two modes of evacuation to shelters (referred as tsunami evacuation buildings) namely pedestrians and cars, and two exits. This study explicitly modelled evacuation travel phase (ESF2) and shelter choices (ESF3) and does not state about the warning dissemination using channels, instead a departure curve using Rayleigh's distribution was used

Based on the literature review, it was found that most of the models are specific to single ESF for example 'traffic congestion models' (Chien and Korikanthimathi, 2007), some have two phases of evacuation explicitly modelled (Stern and Sinuany-Stern 1989, Southworth 1991, Mas et al. 2012a) and other models were with disaster-specific models integrated to it (Charnkol and Tanaboriboon 2006, Lammel et al. 2008, Dawson et al. 2011, Mas et al. 2012a, Mauro et al. 2013). Household behaviour in the three phases can have an impact on the overall KPIs and modelling, this is further investigated in this thesis. However within the evacuation phases (warning to safety) there is potential for further research on developing and using integrated simulation approach for planning evacuation. The choice of OR-based integrated approach corroborates widely accepted purposes of simulation models namely understanding the variability of individual process, interconnectedness and complexity (Robinson, 2003).

Apart from OR modelling being used for evacuation responses, the role of models has been key in the training and exercise for the emergency responders. An integrated gaming and simulation model has been developed to help multi-agency coordination through interactive exercises (Jain and McLean 2005). These gaming tools have visually appealing interface along with the ability for multiple users to simultaneously interact with the system. Any model requires formal training in usage, customization to the evacuation study area and continuous upgrade with changes in study area and policies. Training to the end-users is needed to avoid over-reliance of model output without knowing the assumptions underlying the model (French and Niculae 2004).

The models are not intended to replace the role of practitioner and their diverse experience in responding to emergencies, instead the models support their evacuation plans as an experimentation platform. By involving experienced practitioners in various stages of model development could possibly reveal the knowledge held at individuals to be accessible to others.

OR models have been used for planning various phases of large-scale emergencies; for review see Pidd et al. (1996), Green and Kolesar (2004), Altay and Green (2006), Wright et al. (2006), Simpson and Hancock (2009). As the different phases of emergencies (Figure 2.1) are inter-related and have a cascading effect on the evacuation effectiveness, the EMAs could develop an integrated approach for their preparedness and support the initiatives using analytical models, wherever appropriate. Some of the key gaps identified in literature review are modelling households as warning informants, the impact of ‘warning time and transport choices’ on travel time to safety, shelter information planning modelling various household shelter preferences on shelter allocation. Chapter 3 examines how these approaches informed the methodology used to address these research gaps.

CHAPTER THREE: METHODOLOGY

3.1 **Problem definition**

Modelling large-scale evacuation and particularly the three ESFs require choosing appropriate methodological approach for representing household behaviours and evacuation system (zones, road network, vehicle movement, etc). The aim of this thesis (restated from section 1.9) is to evaluate how 'evacuee behaviour based large-scale evacuation planning of a city can be supported using OR/MS models?' In order to achieve this aim the following research questions have been addressed in this thesis.

Research questions addressed in this thesis

Q1: What is the need for modelling ESFs?

The response to this question has been from the review of literature and gap analyses (Chapter – 2).

Q2: How do household evacuation behaviours impact different phases in evacuation?

The response to Q2 has been addressed using literature review, development of model to address literature gap and model results analyses (Chapter 4, 5 and 6).

Q3: How do household evacuation behaviours affect organisations' evacuation response plans?

The response to Q3 has been done using analyses of model results and scenario experiments (Chapter 4, 5 6).

Q4: How OR-based approach can help GOs in evacuation planning?

Literature review and ERGO findings are synthesised to answer Q4 and subsequently the model developed in this thesis addresses the research gap.

Q5: How OR-based approach can provide an integrated evacuation planning environment?

Synthesised analyses of three model results to understand the interdependencies of ESFs are used to propose an integrated approach for evacuation planning (Chapter – 7).

To address these research questions, key household behaviours have been identified in the literature review of each ESF (Sections 2.8.4, 2.9.7 and 2.10.3) and will be investigated further in this thesis for 'these behaviours' impact on evacuation KPIs'.

- In ESF-1, the household's role as warning informant is to be modelled to measure its impact on warning dissemination.

- In ESF-2, for better managing evacuation traffic what is the impact of household's transport choices (means of transport and destination) on evacuation KPIs? What is the impact of regulating transient traffic on evacuation KPIs?
- In ESF-3, household's independent choice of shelter has an impact on the number of evacuees arriving at a particular shelter. This household shelter selection behaviour will have impact on available capacities in each shelter and will be of interest to the organisation responsible for allocating shelters to different zones.

The above paragraph presented key household behaviour in each ESF and the performance measure of interest for evacuation planners. This chapter is organised in the following manner. The research methodological choices available for the aim of thesis are presented in Section 3.3. As the methodological choices are based on the philosophical position of the researcher, Section 3.3 begins with a discussion on key research paradigms and then the choice between quantitative and qualitative approaches is justified. As this thesis focus is on OR/MS-based evacuation planning, there are a number of techniques available within the field and the comparison of techniques is presented. Section 3.4 ends with the choice of modelling technique for the three ESFs followed by discussion on validation of the models.

3.2 **Research Methodology**

The Oxford dictionary defines 'research' "*as a careful study of a subject especially in order to discover new facts or information about it*". "*Research is about generating knowledge about what you believe the world is*" (Lee and Lings 2008, p6).The word 'research' can be defined "*as an activity undertaken in order 'to find out things' in a systematic way, thereby increasing their knowledge*" (Saunders et al. 2012, p5). Systematic research suggests that it is based on logical relationship and not just beliefs (Saunders et al. 2012, p5). A research is conducted with a specific purpose and to describe/understand/explain/criticise/analyse certain aspects of the subject, and this makes research purposeful. Thus research is both systematic and purposeful.

Experimental research is where the "*causal variables are systematically manipulated to see its effect on the outcome*" (Field 2009, p.15). Correlational research is "*where the co-occurrence of variables is measured without any interference to the system*" (Field, 2009, p.15). One of the features of management research is to "*develop ideas and relate them to practise*" (Saunders et al. 2012, p8). Scientific methodology can be thought of as "*a set of* *techniques about collecting and interpreting evidences which are generally considered likely to illuminate differences in the plausibility of these declarative statements*" (Lee and Lings 2008, p40).

3.3 **Methodological choices**

In research design stage there are various choices that are made and this is summarised in Figure 3.1. The themes of research design (Saunders et al. 2007) are as indicated by the arrows such as philosophies, approaches, strategy, choices, etc. The following paragraphs are presented in the theme of the research design.

3.3.1 Philosophical paradigms of research

Ontology is concerned to "*the nature of reality*" and pertains "*to the assumptions of the researcher about how the world operates*" (Saunders et al. 2012, p130). There are two aspects of ontology namely objectivism and subjectivism. Objectivity represents "*the position that social entities exist in reality external to and independent of social actors*" (Saunders et al. 2012, p131). Subjectivism is the position *that "social phenomena are created from the perceptions and consequent actions of social actors*" (Saunders et al. 2012, p132). Based on these two ontological positions there are two broad classifications of paradigms namely positivism and phenomenological.

Empiricism is based on the view that "*the knowledge we have can come from our observations and that human have no innate ideas which are not from experience*" (Lee and Lings 2008 p28). Positivism believes in obtaining generalizable conclusions based on the observations from the reality, and "*can reach a full understanding based on experiment and observation*" (Ryan 2006, p13). Post-positivism which is a neo-positivist approach focuses on the *"science's account of reality rather than on reality itself"* (Fischer 1998, p135). Phenomenological approaches are based on the view that the world is not external and objective/measurable, rather socially constructed by the observer (Easterby-Smith et al. 2002).

Figure 3.1 The Research Onion (Reproduced from Saunders et al. 2007)

Post-positivism is attributed to Kuhn's ideas on pragmatism and contributions from Feyerabend, Hanson and Toulmin, as cited in Alvesson and Skoldberg (2010, p18). It is also mentioned here that critical alternative world-views against post-positivism and also positivism exist, and readers can refer to studies like Lapid 1989, Patomaki and Wight 2000, etc. This thesis aligns to the strengths of post-positivism philosophy for scientific enquiry. The views of positivism and post-positivism are not opposing to each other (Ryan 2006, p15). There are considerable similarities between positivism and post-positivism (Gephart 1999, Gephart 2004, Table 1, p456). The following are some of the key similarities:

- *Both assume that the reality is objective.*
- *The goal is to uncover truth or true reality.*
- *The main tasks to achieve the goal are undertake explanation and control of variables; discern verified hypotheses or non-falsified hypothesis.*

Unlike positivism, post-positivism holds view that reality can be known only probabilistically and not fully (Gephart 2004). And falsification, not verification, of hypothesis becomes the basic task of research (Gephart 1999, 2004). In post-positivist view, 'pure empiricism is too demanding as the observations and measurements are inherently imperfect, and the objective of science is to try and understand the real word independent of researcher's perception about it' (Cook et al. 1979, Straub et al. 2004). Post-positivist believe that the reality can be known imperfectly and probabilistically (Robson 2002).

Computer models are nothing but a simplified representation of social reality (not the reality itself) created to understand a social phenomenon (Gilbert, 2007). The thesis also believes that "*the reality exists but can never be understood or explained fully, given both the multiplicity of causes and effects and the problem of social meaning..." (Fischer 1998, p143).* This is the underlying principle of 'post-positivism' which has been chosen as the epistemological position of this research. In general computer models of social behaviours (social simulation) are abstraction of social reality to understand the complexity of a social phenomenon of interest, in this case household behaviour for mass evacuation planning of the city. These models are purposeful abstractions including only measurable behaviours of interest, and with reality 'never be fully explained or understood' inline to the post-positivism philosophy.

Based on "hypothetico-deductive method" which describes the relation between data and theory, there are two broad methods and readers are directed to Figure 2 of Lee and Lings

(2008, p41). Deduction is "*the process of drawing conclusions from rational and logical principles*" (Lee and Lings 2008, p6), i.e. Theory →Generate hypothesis →Collect data. Induction is "*opposite to deductive method, is the process of using specific observations (data) and making generalisations*" (Lee and Lings 2008, p7), i.e. Data →make generalisations from data →Theory. The aim of the study, on the basis of ontological and epistemological position of the researcher, would lead to the choice of the methodology (Lee and Lings 2008, p11).

The aim of the thesis is to measure the impact of household behaviours on evacuation planning and specifically using OR/MS tools. In this thesis, the world is considered as objective, reality as measurable though not fully (unlike positivism), with post-positivism philosophy and following a deductive approach. There are two approaches possible for studying the household behaviours of the public namely at a micro-level and at the macro-level.

At micro level the psycho-social behaviour of evacuees could be studied through cognitive modelling to understand the individual behaviours. This approach has been used in various studies (Mileti and Sorensen 1990, Mileti and Peek 2000, Sorensen 2000) to understand how the public would 'understand, perceive and respond to warning messages'. This is broadly a subjective/interpretive approach-based understanding of the household behaviour. The other approach of studying social behaviour is by building models based on "*theoretical understanding and then simulate its dynamics to gain better understanding of the complexity" (Gilbert 2007).* As the household dynamics in the three ESFs are to be studied from the context of evacuation planning at a city level, the latter approach is chosen in this thesis.

3.3.2 Choice between quantitative and qualitative approaches

Quantitative research method is defined as the technique of systematically investigating a social phenomenon in terms of 'measurements' and their relationships in order to 'describe, explain, predict, and/or control the phenomenon of interest'(NCREL 2010). Quantitative methods align with the empiricism as it is based on the assumption that reality is measurable. Qualitative research method is "*defined as an array of interpretive techniques which seek to describe, decode and translate the meaning, not the frequency of certain phenomena in the social world*" (Easterby-Smith et al. 1991, p71). Qualitative methods align with the interpretivist philosophy. As the thesis's epistemological position is post-positivism and aims to measure the household behaviours' impact on evacuation planning, the quantitative research method has been chosen compared to qualitative method. As a city contains many households, which require aggregation of behaviours rather than behaviour of one particular household, quantitative methods provide the framework for aggregation and measuring the relationship.

In the context of evacuation management, this involves measuring various aspects of evacuation (e.g. the time when evacuees receive warning message, travel time required to evacuate, etc) as 'variables' and relationships among them, in order to understand and manage the evacuation process. The evacuee behaviour is represented as quantitative measurable factors at the household level (macro-approach) instead of individual evacuee level (micro-approach). A similar approach of modelling at the household level instead of individual level has been adopted in earlier works (Southworth 1991, Hui et al. 2008, Dawson et al. 2011). This thesis would adopt macro-level approach by developing computer-based models with evacuee household behaviour in order to support the planning of mass evacuation. The micro-level behaviour of the evacuees even though important is not currently addressed in this thesis and this is addressed by a different researcher (Mrs. Susan Anson) in the ERGO team to enable 'public preparedness by using social marketing'

3.3.3 Research method adopted in this thesis

There are various strategies/methods available within the empiricism philosophy, namely experiment, survey and case study. It is not feasible and ethically practical to study 'evacuation planning of a city' through actual experiments. However, computer models provide an ethical means of conducting experiments (e.g. scenarios of disaster impact levels) and measuring the process of interest. Survey is another alternative of quantitatively measuring household behaviours using questionnaires with evacuees. Historical archival data could be studied for supporting evacuation plan on observing the past behaviours. All these three methods are alternatives available to study a particular city and to support an evacuation plan. The pitfall is the availability of survey/historical data with questions of particular interest and the cost of conducting a new survey. However, case study provides a possible alternative to use the data from surveys and archival records, and study household behaviour's impact on evacuation KPIs for disaster scenarios planned. Based on the empirical data and theories on household behaviours in the three phases, this thesis aims at a model-based understanding and prediction of overall evacuation process.

"*The case study is a research strategy which focuses on understanding the dynamics present within single settings*" (Eisenhardt 1989, p 534). Case study method is widely used in the field of operations management (Voss et al. 2002). This thesis has taken a case of a city to present the evacuation preparedness in three ESFs supported by household behaviours. A similar approach has been adopted in various published literatures to demonstrate an evacuation modelling methodology (Rogers and Sorensen 1991, Southworth 1991, Dow and Cutter 2002, Murray and Mahmassani 2002, Kim et al. 2008, Doerner 2009, Ng et al. 2010, Mas et al. 2012b). As the aim of the thesis was to use OR/MS-based evacuation planning, it is important to understand the choices of modelling techniques available within OR/MS.

3.3.4 Choice of OR/MS technique:

In order to model the mass evacuation system, the two broad alternatives available are 'optimization or mathematical programming' and simulation. Mathematical programming or optimization provides the best option among available alternatives and would require a function (in general as an algebraic equation) to model the phenomena under study. There are studies related to evacuee transportation models using network optimization approach (Liu 2006). But the household behaviours in the three ESFs cannot be directly incorporated into a single algebraic equation. Within social simulation there are different techniques namely System dynamics, discrete event simulation (DES) and agent-based modelling (ABM). Readers are directed to Gilbert and Troitzsch (2005) for more information on the individual social simulation methods, its features and comparison. In comparison to ABM's features, different social simulation methods are compared and presented in Table 3.1.

System dynamics is a specific form of continuous simulation that represents a system as a set of stocks and flows (Robinson, 2003, p25). Micro-simulation represents individual units with a set of attributes and behaviours; however it does not have the interaction among the units. "Cellular automata" is a representation of modelled units into grids of cells. At every time step the grid changes its state depending on the neighbours' states. There are transportation models using cellular automata (e.g. Zhang and Chang 2012).

Table 3.1 Comparison of various social simulation methods (Dawson et al. 2011 p171, Table 2)

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Comparison of OR/MS techniques and the choice

System dynamics would be applicable if the overall performance of the system is aggregated through flow rates and levels. As the current level of study would look at the mass evacuation planning of a city considering the individual household behaviour, the system dynamics method is not very appropriate.

The public would undergo different states during evacuation (namely uninformed public, received warning message, choosing the means of transportation and travelling to the shelter). Each of these states has associated behaviour that could be represented using simple if-then rules. DES technique is appropriate for addressing the state changes and not the interactions with other vehicles. In the transportation phase of evacuation, households choose their means of transport (e.g. cars) and enter road network along evacuation route. In this phase, movement of cars will be affected through interaction with other vehicles. Interaction of one household's behaviour with others being the key will not be provided by DES modelling framework alone. Thus, system dynamics and DES are not appropriate for modelling the household behaviours with interaction.

Simulation models are widely used as an experimental research technique where the input parameters in the model are systematically varied to study the performance metrics (output variables). During large-scale emergencies there are two broad categories of uncertainties: behaviour of evacuating population and implication of EMAs response action on evacuation. "*Simulation has been shown to be an effective method for handling this problem of unpredictability during evacuation and in anticipating and creating an efficient response procedure to it.* " (Chen et al. 2012, p207). For example, EMAs would want to know the effect of evacuee behaviours (e.g. means of transport) on the successfulness of evacuation measured using ET. In this case, a simulation model can be used to change this factor and study its impact.

It can be observed from Table 3.1 that, ABM is the only framework that provides spatially explicit, heterogeneous capability with communication among agents. The choice of the Agent-based modelling is very appropriate for the aim of the study i.e. to model the behavioural aspects of the public during three ESFs. Mapping of agents to evacuating household provides an easy platform for modelling ESF phases. This approach has been adopted in earlier work to model evacuation of regions of the city (Rogers and Sorensen 1988, Mas et al. 2012a). The modelling of traffic has been adopted using network optimization approach (Cova and Johnson, 2003) by modelling road as 'links' and junctions as 'nodes'. In this approach, the evacuee behaviour is depicted using flow rate (number of vehicles/time) instead of individual cars. This thesis would adopt combining network representation of the road (network model), evacuee state (represented as discrete states) and vehicle driving (as agents). Thus by combining various approaches to represent the evacuee behaviour makes the model more realistic unlike earlier approaches. The thesis would also propose an integrated approach for mass evacuation planning of the city instead of ESF-specific preparedness that does not explicitly consider inter-linkages.

A critique on the ABMS is that the approach is based on methodological individualism where each agent represents an individual and reducing all social structures to individuals (O'Sullivan and Haklay, 2000). In cases where there is lack of theoretical underpinning of the social structure, the interaction of the agents in the model, and not explicitly identifying the assumptions of the model, would lead to incomplete representation of the society (O'Sullivan and Haklay, 2000). This thesis will develop ABM with the behaviours identified in the available literature in social simulation on mass evacuation. A model is an abstraction of specific features of the real world. The models developed are from the practitioners' perspective and would include the behaviours of the public identified as relevant by the IAB panel. The three models characteristics were presented to the advisory board to review the appropriateness of variables chosen for evacuation planning. This will address the theoretical and practical relevance of the model. The model was further validated during the feedback visits to ERGO countries to present the findings as well as illustrate OR-based evacuation planning. The following paragraphs provide brief details of methodology choice for the three ESFs.

Choice of OR/MS technique for ESF-1(Warning Dissemination)

Evidence from the post-disaster evacuation suggests that the houses receive warning from their network including neighbours. Existing body of knowledge argues about the role of unofficial warning channel as voluntary or coordinated/planned system of warning dissemination. This thesis aims at answering 'what is the impact of the household neighbour informant behaviour on warning dissemination?' In order to support empirical evidence, a modelling approach has been chosen to incorporate the household behaviour (micro-behaviour) and understand the warning dissemination of the communities/city regions (macro-behaviour).

Agent-based modelling is often chosen to develop model-based understanding of individual units (say houses), their behaviour and its implication on the system's (evacuating regions of a city) phenomena of interest (warning dissemination). This approach assumes that the 'behaviour of household in warning their neighbours' is empirically measurable and represented in quantitative units, derives the aggregation process of understanding the 'system' through development of behavioural analyses of warning response states through process maps and uses that process for aggregation from 'units to system'.

Choice of OR/MS technique for ESF-2 (Evacuee transportation)

Simulation models for the movement of traffic could be classified (Southworth 1991) as 'micro-simulation' (where the individual vehicles are tracked) and also 'macro-simulation' (looking at the stream of vehicular flow). 'Dynamic Traffic Assignment' models are macroscopic models where the departures are not decided at the household level instead they use zone-wise loading curves. On the other hand, microscopic models simulate evacuation phases at each household and after departure simulate the behaviour of vehicles on roads. One of the examples of microscopic and yet large-scale evacuation model is for the city of Padang, Indonesia, for tsunami preventive evacuation (Lammel et al. 2008). This thesis would adopt the micro-behaviour of the individual vehicles but not the individual evacuees while developing the ABMs.

The implementation of simulation clock advances is a key component in a simulation model including transportation models and there are two methods.

- Time slice-oriented method uses pre-defined time unit for regularly monitoring the states of the model units (e.g. a vehicle) and update to a new state.
- Event-oriented method computes the time needed for change in state (event) is computed for each unit and then the state is updated.

Formulation of event-list for a transportation model involving few thousand vehicles in a city-scale road network makes event-scheduling algorithm to be more complex. Hence, time-slicing method is preferred in this thesis. Thereby, the states of 'leader follower' pair are regularly updated using the car-following logic. For the transportation model, the time slice value in existing traffic simulators is often 1.0 seconds (Schulze and Fliess 1997, p1224). Smaller the value of tick, larger the number of iterations and more will be the model execution time.

Choice of OR/MS technique for ESF-3(Shelter management)

Traditionally, optimization techniques are used to obtain the best solution by solving the problems that follows standard structures. As there is a need for minimising the TET (time from departure to safety) of all the evacuating zones by optimally allocating the available shelters to the estimated demands from different evacuation zones, optimization is a suitable OR technique for solving the problem. Here the objective function and the constraints are linear in nature; thus the shelter allocation model formulation belongs to LP problems. This is in-line to the approaches used in the existing literature (Sherali et al. 1991, Kongsomsaksakul et al. 2005, Ng et al. 2010).

It is anticipated that the results of this model will be a positive integer (whole number), indicating the number of evacuees among the estimated demand to be allocated to different shelters. As the decision variables are integers, this leads the problem to be of a special class of LP namely Integer Programming problem (IP). The solution space (comprising all the possible values for the decision variables) will be a grid of points in the IP problems on contrary to a polygon area in the LP problems. This highlights the computational need and special algorithm for arriving at the optimal solutions in the grid within minimum computational time, though an interesting topic will not be covered in this thesis. This thesis will use the existing solver in the MS-excel for solving the IP problem.

Incorporating the evacuee behaviour as quantitative factors into simulation models is acknowledged as a challenge in terms of model validation. The evacuee behaviours has been represented in the previous study (e.g. OREMS, Southworth 1991) using proxy variables such as delay time in preparing to evacuate, choice of evacuation transport and car-driving behaviour. All these quantitative variables serve as a proxy for the evacuee behaviour relevant to mass evacuation planning. Some of the numerical values will be identified from the actual events, academic and practitioner literature and would be used as a representative value in the model. The behaviour of the public can be studied using interpretivist approach to identify and group similar group behaviours. This thesis has incorporated such findings from published sources along with the expert panel judgement using IAB to identify the public behaviours relevant for planning mass evacuation and then develop the models. Any model is an abstracted representation of reality and hence it is important to test the validity of the model in comparison with reality.

General principles of Verification and Validation of a model

Model 'verification' and 'validation' are two important portions of model development process (Sargent 2005) for ensuring the reliability of the model findings (Sargent 2005) and increase the end-user confidence (Robinson, 1997). Model validation is defined as "*substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model*" (Schlesinger et al. 1979). The model validation will be carried out at various stages (Kleijnen 1995) namely

i) Conceptual modelling stage (by identifying and using published modelling approaches to incorporate evacuee behaviours)
ii) Model development (by one-to-one demonstration with senior practitioners in critiquing the validity and completeness of the model features. Apart from that, the model development during the feedback visit to the ERGO countries would also be used to measure the validity of the model, usefulness to the practitioners and to identify features for further development)

iii) Sensitivity analysis (for the factors with less reliable numerical value and also considering the cultural aspect of the evacuees, the model would be studied for a range of values to understand the sensitivity of the model input)

Model verification is defined as "*ensuring that the computer program of the computerised model and its implementation are correct*" (Sargent 2005). In the coding stage, the model was verified through code review and unit testing of modules. After coding, the model was tested for each functionality through unit testing (individual modules) and system testing (collectively after integration). The rigorousness of the model development will ensure the reliability of the model results by the stakeholders as well as the contribution to evacuation modelling theory.

Verification of model during development was done through recursively testing the modules and ensuring the implementation. Unit testing was carried out in each module of the three models. System testing was conducted after integrating all the modules of a particular ESF and repeatedly testing model through many runs. For ESF-1 and ESF-2, the implementation of behavioural modelling in ABM was done in two phase. The first phase involved implementation and testing code in a simplified case (prototype) and second phase was for ERGO city. This phased development provided control over the code development and improved accuracy by testing/debugging the logic in a smaller scale.

The validation of the models was been done in thesis at various stages and can be broadly classified into three categories: academic review (AR), emergency practitioner review (EPR) and IT systems expert review (ITR). Managing simulation model development as a simulation project will ensure reliability of the model. The implementation of the conceptual model as a software code requires validation.

AR and EPR were conducted with expert academics and practitioners provided opportunity to review the model development with the existing state of the art. The ITR was conducted in this thesis by an expert in the field of developing software applications. Given the conceptual model and model objective, the implementation of the code was reviewed. Inline to the three broad classifications, the validation of the model was carried out in various stages as presented in Table 3.2.

This thesis found that the overall experience of using ITR for the developed models provided considerable help in transferring good practices from an experienced IT specialist in helping to increase the reliability of the developed model. In a large-scale coding project, providing easy readable and meaningful names for variables and procedures is a good practice in software coding. During the initial review, the module names were not easily readable and hence changed, and this was one of the learning from this thesis and a valuable outcome of ITR. This thesis argues that such an approach has a potential for strengthening the reliability of the model by: benchmarking the research with academic rigour, ensuring good practices in IT to be implemented in evacuation modelling, and developing usable and realistic evacuation models for planning ESF response.

The model interface was developed as a user-friendly tool to enable the practitioner for building and testing various scenarios and assumptions for mass evacuation planning. This thesis intends to develop a tool that would support the decision makers at the planning stage to test various scenarios, training and table-top exercises. The model is not intended to be used while responding to an emergency as the response is based on experience and standard operating procedure for various organisations.

Table 3.2 Validation of ABM in this thesis

STAGES	CLASSIFICATION		
	AR	EPR	ITR
International Advisory Board - 1		✓	
ESRC Seminar held in Aston University	✓		
POMS Conference	✓		
International Advisory Board – 2		✓	
Master Class		✓	
ICEM conference	✓	✓	
Proceedia Engineering – Journal Publication	✓		
European Journal of Operational Research (EJOR) – Journal publications	✓		
InterCEPT conference	✓	✓	
Feedback presentations in ten countries		✓	
ESRC Seminar held in Cranfield University	✓		
Peer Review by Dr. Adam Zageroecki	✓		✓
Peer Review by Koen De Budt (IAB member: Brussels)		✓	
Peer Review by Kevin Arbuthnot (IAB Chairman)		✓	
Peer review by Senior Software Developer			✓

Choice of Modelling Software

The integrated evacuation model (iEM) developed in this thesis has three modules corresponding to three ESFs. Three modules of the iEM use two OR/MS techniques namely ABM and optimization. In this thesis ABM was developed using NetLogo software. There are other ABM modelling platforms such as Repast Simphony, MASON, Core Java APIs, and StarLogo (Macal and North 2009, p94). The ease of use for the non-IT savvy emergency managers makes NetLogo appropriate. In their review of agent-based modelling platforms, Railsback et al. (2006) considered Netlogo as the ‘‘*highest-level platform, providing a simple yet powerful programming language, built-in graphical interfaces, and comprehensive documentation*". One of the disadvantages of NetLogo is the limited flexibility in generating output graphs interactively by the user and this has been handled by writing 'standard output reports' as a sub-routine.

There are various platforms for optimization such as Lingo, LPSolver, Matlab, etc that provide inbuilt functions for solving IP problem after formulation. However, the IP problem is to be formulated based on ABM outputs from ESF-1 and ESF-2 for a specific scenario experiment and hence Visual Basic Applications (VBA-Excel) provided a suitable programming framework and optimization solver for developing SIMS model.

It was not feasible to integrate an ABM simulation model (NetLogo) and optimization in a single modelling environment. There are Java APIs available for many operational research techniques including ABM and optimization, which could have facilitated the integration by either developing iEM from scratch in core-java or possibly extending Repast. Since NetLogo does not provide interface for integrating optimization macros, the choice of NetLogo enabled only semi-integration.

A case study provides a single setting (i.e. evacuation region) to understand dynamics (e.g. household behaviour) and study a process of interest (i.e. evacuation performance). ABM provides a framework for representing household behaviours as agent behaviour and studying the impact on the system (i.e. overall evacuation performance). The next section discusses how the data needed to address the research question was designed and obtained.

3.3.5 Data collection and analysis

An overview of the ERGO Project and the framework was presented in Section 1.3. The data collection for answering the objective of ERGO project was done through 97 semi-structured interviews conducted from November 2008 to May 2009, with each interview lasting around one hour. In the ERGO project, the interviews were analysed to identify metrics that could be used for measuring the government's preparedness and also repository of analytical models that are currently used by the participant countries. As the thesis focuses on models used for ESF planning, the transcribed interviews were used to document findings for each participant country on 'the models currently used, warning/transport/sheltering policies, and planning assumptions'. In chapters 4, 5 and 6, these ERGO findings are presented respectively on the three ESFs. In addition to the gaps on ESF models identified in literature, these findings provided gaps for further model development in this thesis.

This thesis makes an independent contribution by studying the potential for using computer-based simulation models for evacuation planning for a city. This thesis focuses on developing computer models for warning message dissemination, evacuee transportation model and shelter management, namely elements 4, 5 and 6 in Figure 1.2. The other elements (1, 2, 3) in the integrated model would be addressed by other researchers in the ERGO team (Dr. Paul Kailiponi and Mrs. Susan Anson).

Quantitative data – An introduction

Quantitative data are represented in the form of measures (variables) that can be broadly classified as 'independent variables' and 'dependent variables'. In the context of cause effect relationship, dependent variables are influenced by the independent variable. For example, in transportation management, the choice of evacuee transportation (independent variable) (e.g. using cars) will influence the TET (dependent variable). These variables form the basic unit of building quantitative models based on the relationship between dependent variable (ET) and independent variable (choice of transport). Quantitative data forms the basis of developing evacuation models. The Quantitative Modelling approach has been used for more than five decades (Simpson and Hancock 2009) in supporting evacuation management. These models are used to understand the variation of the independent variable and its effect on the dependent variable. The ERGO interviews and the literature were used to identify quantitative variables for modelling evacuation preparedness. For example, during the interviews, it was found that the EMAs in Hamburg specified that the 40% of the evacuating public will use public transport and others will be self-evacuating in cars. This quantitative data was helpful in identifying the 'type transport usage (%)' variable as well as a representative value for it. The variables and their interrelationships were identified for each phases of the evacuation and are elaborated in Chapter – 7.

Sources of quantitative data

Quantitative data were collected from different sources during the ERGO project namely transcribed interview data, evacuation plan documents, observations during site visits, secondary data from reports, surveys and model demonstrations. Coding schemes were used to analyse the transcribed ERGO interviews. For each phase of the evacuation model, the content was further analysed to identify the evacuee behaviour and EMA response factors, and document representative values for these variables. In case the representative values for the variables varied to a wide range, descriptive statistics (e.g. mean and standard deviation) were used to represent the variation. The same approach has been used to analyse the evacuation plan documents and leaflets.

Apart from the data collected from the participant ERGO countries, published literature (both academic and practitioner), post-disaster reports, pre-disaster studies and evacuation manuals form an important data source for identifying the variables as well as representative values to support evacuation modelling. Survey data forms an important data source for supporting evacuation preparedness. Table 2.1 presents different types of data source. During the ERGO data collection process, the countries were requested to provide survey results that they have used for evacuation planning, and this was used to identify the generalisable planning aspects and make it transferable to other countries.

The sequence of events in the evacuation plan (e.g. warning dissemination phase) is another important data source. This data will be collected as a 'process map' for individual phases of the evacuation based on the interviews and evacuation plans. A'process map' (or conceptual model) is defined as a "*diagrammatic representation of process in order to provide better understanding"* (Greasley 2004, p52) of the system under study. A process map consists of a set of variables and a set of logical and quantitative relationships between them (Lee and Lings 2008, p125). This process map would help in developing models of the evacuation process in order to support evacuation preparedness. For example, the sequence of events between warning message and evacuees leaving the house could be represented as a 'process map'. An illustration of a process map based on the literature was presented in Figure 2.1. This following sub-section presents the ERGO city case study used to illustrate integrated evacuation planning.

ERGO City Case study

The three ESFs covered in this thesis are common across many disasters. However, as an example of a rapid-onset disaster, a flooding scenario was chosen for demonstration the models. This thesis has taken all-hazards approach for developing the model. The disaster impact is inputted to the model as 'zones to be evacuated'. The disaster event is taken to be outside the boundary of the model. While using these models to a real-life city, the planned threat/hazard and the scenario can be inputted as evacuated zones. The IAB members served as an expert panel in validation of the scope of the model. The findings from the ERGO study along with the models developed as a part of this thesis have been presented to the participant countries during subsequent visits.

The ERGO city case study will be used to highlight some of the response strategies that could help the planners to contextualise the model to their city. ERGO city is a multi-ethnic modern city with a resident population of 1.6 million people. The city is well connected by three major expressways serving to the resident population and commuters (0.5 million) for the booming business district. The central area of the city indicated by A4-A5, B4-B5 and C4-C6 (refer to Figure 3.2) is home to three universities as well as the business district. The city is prone to storm flood and the EMA have been preparing both the organisations and the public for potential large-scale evacuation.

After considerable rain during the winter, the environmental agency (EA) had warned about the potential breach of dykes and they have been monitoring the water level very closely. EA using their 'River Flooding model' has identified the areas that need evacuation and sent the following message to the multi-agency committee for evacuation decision.

There was a major emergency in the 'flood zone' areas of the ERGO city. The areas indicated in blue in the ERGO city map are likely to be inundated. There is high possibility of the flood protection dykes to break within 1.5 hours.

Considering the flood forecast from the EA, the multi-agency decision-making team has decided to evacuate considering the safety of the public. This multi-agency team includes local authorities, police, transport officials, Red Cross and humanitarian organisations. The GOs are responsible for implementing the decision by supporting the evacuation. These EMAs as a preparedness initiative have developed an 'evacuation plan' as well as 'organisation level response plans'.

For the context of ERGO city, other evacuation options such as in-sheltering and vertical evacuation are considered as infeasible given the high level of flood and duration to last for few days. As the evacuation begins from relocating the public at-risk to safe place outside the evacuated zone, this thesis will cover three EFSs namely: ‘dissemination of warning message, evacuation transport management and managing emergency accommodation’.

Police officials in the ERGO city are responsible for dissemination the warning message for evacuation. In the warning preparedness section of evacuation plan, they have identified TV, radios, mobile messaging, landline message and sirens as the official channels used for warning the public during evacuation. As a policy, all these channels will be used in tandem to reach out as ‘everyone’ as ‘quickly’ as possible.

There are 19 zones to be evacuated indicated by blue zones in the ERGO city map. There are about 32,000 households living in the evacuated region. The evacuees can evacuate using cars and the transport officials will also provide bus facilities for the needy. The transport authorities are responsible for managing the evacuating traffic and implement response strategies that support a speedy evacuation.

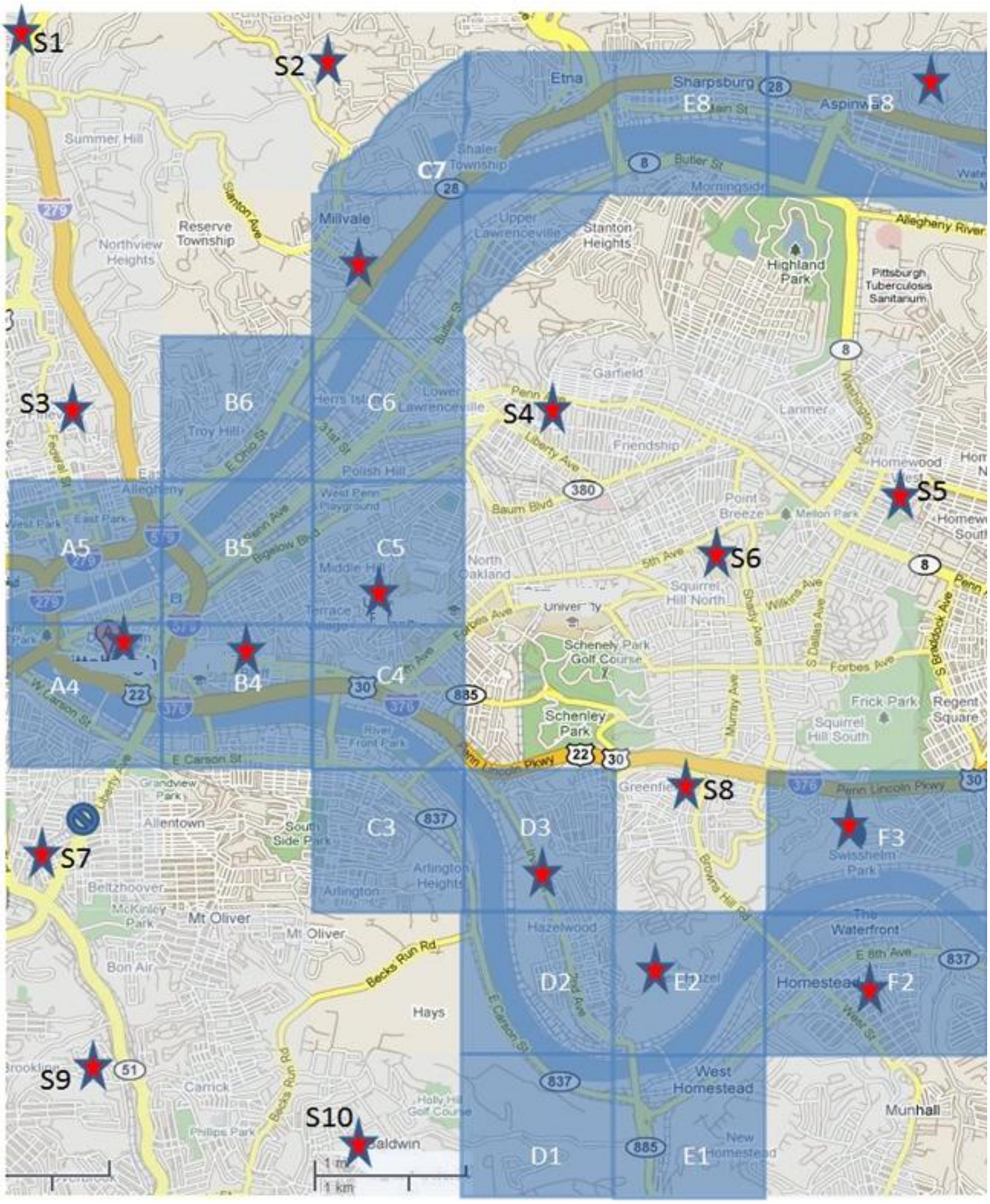


Figure 3.2 Snapshot of ERGO city with zones to be evacuated due to flooding

Local authorities have identified potential locations for 'public shelters' in advance throughout the ERGO city. Due to the level of flood in the evacuated zones, the shelters within that zone are considered to be unsafe. The shelters available in the neighbouring 10 boroughs (represented by a star symbol S1-S10) are available for receiving the evacuees. Figure 3.3 shows the overall architecture of the model. The architecture enables a generic modelling platform to customize data from other cities. Further details on 'the ERGO city relevant for each ESF' are presented respectively in chapters 4, 5 and 6.

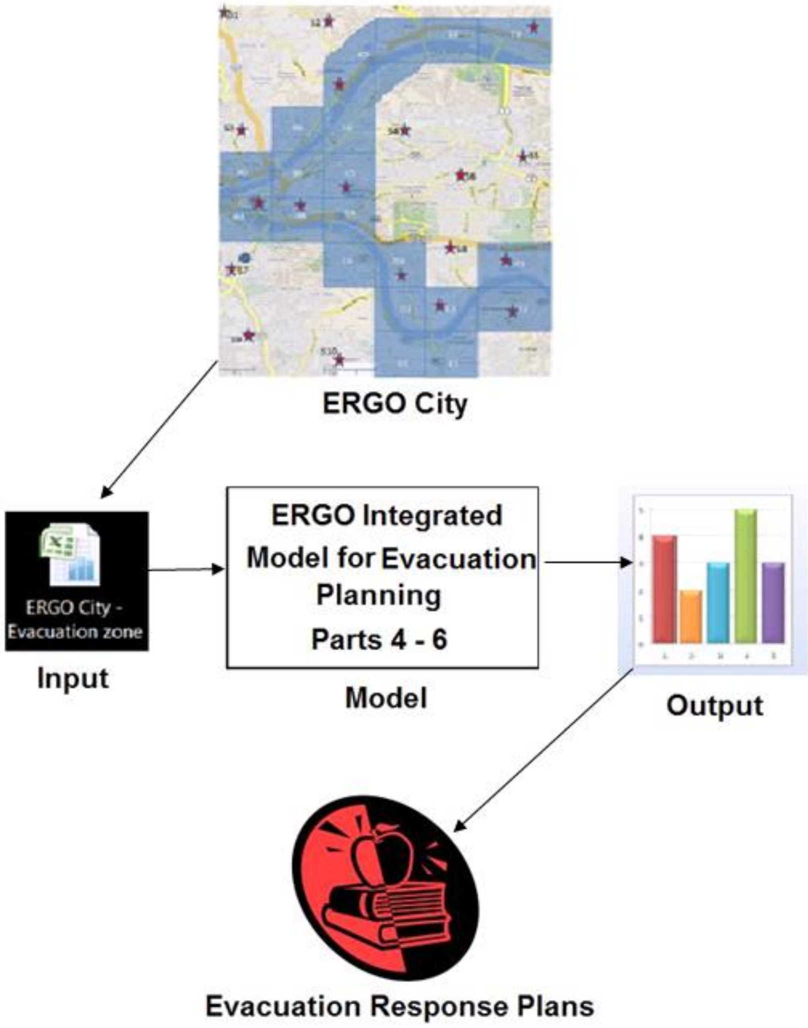


Figure 3.3 Overall modelling architecture for parts 5 and 6

3.4 **Research design of the thesis**

In line to the framework proposed by Saunders et al. (2007), Table 3.3 presents the choices made at various stages in research design of this thesis. Table 3.4 consolidates different techniques that were used for the three ESFs.

Table 3.3 Research design choices

Research design element	**Choice**
Philosophy	Post-positivism
Approach	Deductive
Strategy	Case Study
Method Choice	Multi-method
Data Collection	Secondary data

Table 3.4 Modelling techniques used for each ESF model.

ESF Phase	**Techniques used**	**Level of modelling**
Warning message dissemination	Agent-based simulation	Household - mesoscale
Evacuee transportation model	Network models and agent-based model	Household as a Vehicle/pedestrians – mesoscale
Shelter management	Optimization	Household – mesoscale

Warning, transportation and sheltering does not happen in isolation. Rather, these are phases for the household to move from danger to safety. This thesis will look from the perspective of evacuation preparedness of supporting GOs at the journey of the evacuees from the onset of evacuation warning to their relocation to safety. Evacuation is supported by different organisations (GOs) in various evacuation phases with separate organisation level evacuation plan. Instead of planning for evacuation as individual phases, this thesis will adopt an integrated approach of studying the interconnectedness of the GOs, their response plans, and cascading effects. The ‘inter-agency coordination’ is one of the major pitfalls from Hurricane Katrina experience. This thesis does not recommend replacement of individual organisation level preparedness, which is essential, instead strengthening it further through OR models.

There are various planning assumptions about the evacuees that form the basis of evacuation plans. At times, the GOs hold some beliefs about the evacuee behaviour choices implicitly through their experience. Some of the evacuee behaviours are influenced by the existing laws (e.g. cannot evacuate using cars) and policies (e.g. no public transport support). There are uncertainties in the behaviour of individual evacuating household which can have an impact on the overall evacuation. An OR evacuation model will serve as a platform for the GOs to understand the implication of the various facets of evacuee behaviours including their planning assumptions, long-held beliefs, influence of laws and policies and uncertainties on the overall evacuation.

On a contrary argument, there are uncertainties in the household behaviour, no accurate empirical evidence exists and yet EMAs require empirical evidence to support their evacuation plans. Acknowledging these limitations, the role of model is emphasised much more in the absence of enough information. Uncertainty in the modelled phenomena (parameters, behaviours, system boundary, etc) can be tested through sensitivity analyses with the model and develop model-based understanding. In general, "*the purpose of models is to simplify complex situations so that they can be understood adequately*". (Alexander 2009). Once a model is developed and tested and conclusions/findings are generated about the phenomena of interest, it is not an end, but a beginning of the next cycle of model development.

No model is a perfect representation of reality nor is the knowledge about evacuation process complete. With increasingly complex disasters (e.g. 2011 Tsunami in Japan) and the EMA's ability to respond through better planning, designing response strategies and judicious use of resources, understanding about the evacuation is argued to be progressive. A model serves as an ethical means of testing the preparedness initiatives than trying during an actual event. With the ERGO city case study approach, chapters 4 to 6 present the model development for three ESFs, then followed by an integrated approach for evacuation planning (Chapter 7).

CHAPTER FOUR: MODEL DEVELOPMENT - WARNING MESSAGE DISSEMINATION

4.1 **Evacuation warning message dissemination – An introduction**

During the tsunami in Indian Ocean (2004) about 230,000 people died. 'Telegrafia® warning system' leaflet claims that *'if there was a warning system, about 80% of them could survive'* (Telegrafia, 2010). The tsunami disaster has showed *'what happens when an effective warning system is not in place'* (Sierra 2006, p.3). In a large-scale disaster providing timely notification to the public about the threat is very essential to save lives. This thesis focuses on the three ESFs namely 'disseminating warning to the public' (Chapter 4), 'transporting the evacuees from evacuated area' (Chapter 5) and 'managing public shelters' (Chapter 6), and supports these ESFs planning using ORMS-based approach. This chapter begins with the key findings from the ERGO project data and then followed by the model developed to support warning dissemination planning for the GOs.

4.2 **ERGO project findings on warning message dissemination (ESF – 1)**

The following section presents the findings on warning dissemination based on the data collection of the ERGO project. The organisation responsible for warning dissemination was commonly found to be the police in the ERGO participant countries. Depending on the nature of disaster, there are other organisations that provide key information for the warning content. For example, in the evacuation during the storm flooding in Germany, the 'Hamburg Port Authority' played a pivotal role in providing the severity information to the 'Ministry of Interior' for disseminating evacuation message. Warning systems are comprised of 'formal channels' and 'informal channels' as discussed in the literature review (Section 2.8.2). The ERGO findings on warning dissemination are grouped into these two categories and presented below. During the interviews, it was found that, in many ERGO countries, warning messages are disseminated to the public using a variety of low-technology 'formal channels', such as: telephones, television, radio, sirens, route alert using cars and public announcement (PA) systems. These formal channels are common across all the participant countries, and there were other formal channels too. These will be discussed in the next sub-section.

4.2.1 Findings on warning dissemination using 'formal channels'

In Germany, 'church bells' were used as a warning channel to alert the public. As the density of population is low in Iceland, 'fire crackers' were also used in mountainous areas to alert the public as well as tourists about a potential emergency. It was also found that the billboards in prominent tourist places mentioned fire crackers as well as the nearest evacuation point. 'Door-to-door knocking' by uniformed police officers was also used in highly vulnerable areas in Germany, United Kingdom, Iceland and Denmark. During the preventive evacuation for Cyclone Yasi (2011) in Australia, police officials employed door-to-door knocking in the low-lying storm surge areas of Townville and Cairns (Brisbane-Times, 2011).

Belgium has 'radio alarm receiver systems' installed in the houses within the inner zone (within 10km) of the Tihange nuclear plant. These radio systems can be remotely activated and has a backup power using battery to switch-on automatically even if it is disconnected to power supply or there is electricity failure. A similar system was available in Sweden too. Japan has a network map that shows the coverage of PA alerts that use fixed speakers installed across a city. Based on the coverage, a higher number of PA systems are installed in densely populated areas in order to reach the public in urban and semi-urban regions. A similar system of PA networks is managed for typhoon threats in the region of Hallands Lan in Sweden.

Apart from these conventional official warning channels, there are other technology-sophisticated warning channels too. Belgium has the Domino-Gedicom system (Langloy 2006, p.2) which is a telephone network-based warning dissemination service that can be used to disseminate warning message to landline phones for a selected evacuation area. This system has been used in training and exercises by testing the warning level using mass auto-dial to telephones. During the ERGO master-class presentation it was found that, Norway uses a UMS 'population alert' system for quickly delivering alerts to 'landline and mobile' based on the location and address of the selected region. This product is sophisticated enough to identify and categorise the telephones of non-residents including foreign tourists and can disseminate warning message in their native language. It is observed that there may be privacy and legal restrictions in some countries (e.g. Data Protection Act in the United Kingdom) that may hinder adoption of such technology solution as a warning channel.

The Environment Agency (EA) in the United Kingdom has a ‘subscriber-based’ flood warning system where the residents of flood plains can receive free flood warnings to their landlines. The residents can additionally sign-up for receiving alerts to their mobile phones as well as email updates. The EA also has a dedicated ‘floodline’ telephone service to advice on queries from the residents regarding flood preparedness. Apart from these, the EA website has a facility for users to get detailed forecasts for their locality, and this information is updated every 15 minutes. Table 4.1 summarises ‘official warning channels’ found during the ERGO data collection. Broadly, the official channels can be grouped into conventional channels (e.g. media channels and warning network installations), localised warning units and technology-based high-tech systems.

Table 4.1 ERGO findings on official warning channels in the ERGO countries

Sl.No.	Official channel	Group	Feature (if any)
1.	Television	Conventional channel	Media channel
2.	Radio	Conventional channel	Media channel
3.	Tone alert systems	Conventional channel	Voice and tone alert systems
4.	Telephones	Conventional channel	Auto-dialler systems
5.	Church bells	Localised warning units	
6.	Fire crackers	Localised warning units	
7.	Door-to-door knocking	Localised warning units	Manual warning of household typically by police officers
8.	Public announcement networks	Technology-based systems	Remotely controlled PA units
9.	Radio alarm system	Technology-based systems	Automatic remotely activated alarm system
10.	Domino-Gedicom system	Technology-based systems	Satellite-based auto-dialler for landline and mobile
11.	Unified messaging service	Technology-based systems	Location-based auto-dialler alert systems
12.	Subscribed based systems	Technology-based systems	User can opt in and out of a warning messaging service
13.	Flood line – hotlines	Technology-based systems	Hotline telephone numbers for providing information to the evacuees

4.2.2 Findings on warning dissemination using 'informal channels'

Apart from these formal channels, community-based informal channels, where the evacuating members act as informants, are also used in warning dissemination. It was found in the ERGO project that, Iceland uses community involvement in a 'runner-follower' warning network, where each evacuation zone has few runners (volunteers) pre-identified, who would verify the evacuation of neighbouring residents en route by checking for signboards left in the houses' window after their occupants have left. During the preventive evacuation (April 2010) of volcanic eruption in Eyjafjallajokull, this runner-follower system was proven to be very effective both by the emergency responders and by the evacuated public interviewed by the ERGO team from the Hvolsvollur region. This is a good example for using the community as a resource and a 'coordinated unofficial channel' for warning dissemination, and the successfulness of this system was evident from the recent evacuation.

The use of informal social media such as 'blogs, Face-book and Twitter' was found during the 2010 volcanic eruption in Eyjafjallajokull in Iceland among the evacuees. Apart from informal warning among the evacuees during the Cyclone Yasi evacuation (February 2011), Queensland police officials in Australia have reached out 'instructions for evacuees' through Face-book and Twitter. This illustrates the use of internet or social media as a means of informal warning dissemination among the general public. Table 4.2 summarises the ERGO findings on informal warning channels.

Table 4.2 Findings on Informal warning channels in the ERGO countries

Sl. No.	Informal channel	Feature
1.	Runner-follower	Volunteer based
2.	Flood wardens	Pre-identified and trained wardens
3.	Informal social media	Blogs, Face-book and Twitter

4.2.3 Testing evacuation warning systems as an evacuation preparedness initiative

The EMA responsible for warning dissemination needs to test their warning systems at the planning stage to strengthen their preparedness. The testing is intended to measure the time needed for warning, generate awareness among the public and also ensure functioning of warning instruments. The Gedicom-Domino system used in Belgium has a facility to test the telephone-based warning dissemination within the software without actually dispatching the message. In Denmark, the sirens are tested every year, and the meanings of various sirens were conveyed to the general public. In Germany, during the annual flood day exercise official sirens were displayed to the general public and also tested. Japan has developed the OWASE software to model the tsunami warning dissemination as well as estimating the likely casualty for a chosen level of tsunami (OWASE, 2013). This model was developed based on 'multi-agent simulation' technique and was found to be helpful in planning warning dissemination. It was also found that the warning dissemination to the vulnerable population (e.g. people with visual and hearing disabilities) requires further research. No single warning channel can fully provide timely warning and full coverage to the evacuees, and it was evident from the ERGO interviews that the GOs across the participant countries used as many official warning channels as available.

Authorities responsible for warning the public use official warning channels to disseminate the warning message. Apart from the official channels, literature as well as the findings from the ERGO countries (particularly 'runner-follower' model of Iceland and Flood wardens of United Kingdom) highlighted the use of community-based unofficial warning channels. An OR based warning dissemination model has a potential to empirically study the effectiveness of warning systems (official and unofficial) and also the impact of uncertainties in timely warning. This thesis provides a modelling platform for measuring the effectiveness of warning dissemination by integrating official warning channels along with the unofficial warning channel particularly the warning dissemination among neighbours. The model will be used to illustrate the effect of time of the day on warning dissemination and the potential impact of using informal channels. This model will help the GOs to plan, test and exercise warning dissemination process as a part of preparedness initiatives.

In summary, apart from the functional testing of warning channels and generating awareness to the public, it was found that there was no comprehensive testing plan for warning dissemination among the ERGO countries. During the literature review on warning dissemination, there were many studies that highlighted the potential for using simulation models for warning dissemination planning, and none of ERGO countries were found to use such analytical tools. There is evidence from the post-evacuation studies on the importance of the role of unofficial warning channel as well as community involvement in warning dissemination in the ERGO countries, but this has not been empirically studied to support unofficial channel as a warning channel with evidence base. Modelling the effectiveness of warning dissemination by integrating the official and unofficial warning channel remains unexplored.

4.2.4 Research gap on planning for ESF-1

In the city of Padang, Indonesia, 'expected warning time' is only 30 minutes for Tsunami waves to reach the shoreline (McCloskey et al. 2008). This is an example of rapid-onset disasters with a very narrow time available from warning to evacuation. Using ABM developed in MATSIM, it was found that for the overall ET by foot was 75 minutes (with 30 minutes warning time) for the evacuees to reach safety (Lammel et al. 2008). This highlights the role of models in warning time for evacuation preparedness.

The literature review had highlighted various factors affecting the warning dissemination, namely: effectiveness of the warning channels, potential vulnerability of warning channels during the disaster (e.g. telephone network failure), scope of using 'informal networks' for warning dissemination, and 'time of the day' when evacuation order is issued. These are important preparedness aspects for the GOs responsible for providing timely warning and remain unaddressed in considering the factors in the warning plan. Official channels cannot reach all the members of a community, and hence unofficial channels are also important. Even though the ERGO findings indicate 'coordinated unofficial channels' (e.g. Runner-follower model of Iceland) similar to the flood wardens of the United Kingdom and the literature has already identified the role of unofficial channels including voluntary/Uncoordinated dissemination (Parker and Handmer 1998) and evidences for spontaneous message dissemination in absence of official channels (e.g. evacuation due London sub-urban fire accident), the level of the public as informants and its uncertainty need to be investigated as a potential informal warning channel apart from official channels.

Parker and Handmer (1998) highlighted that the effectiveness of the unofficial warning channel 'cannot be assumed to be the same across different cultures, levels of social and economic development' and hence any quantitative estimates of dissemination need further examination through sensitivity analysis. Irrespective of either uncoordinated or coordinated unofficial dissemination of the warning message, the behaviour of households should be understood to inform emergency planning.

For a household to be a warning channel, there are several choices to be made at the household level (e.g. whether to warn neighbour or not?), and these household choices would impact the overall warning dissemination at a city scale. This thesis will develop a simulation model integrating 'official channels and unofficial channels' that could support planning and testing the warning message dissemination to the public. The model will be used to investigate the uncertainties in unofficial channel and its impact on warning dissemination.

4.3 **Model for warning message dissemination – An introduction**

Warning systems 'warn' the public under threat before/during an evacuation and some 'inform' them of actions to carry out to protect themselves and others. The need for quick dissemination of the warning message is essential for no-notice disasters like earthquakes, tsunamis, flash floods, tornadoes, industrial accidents and terrorist attacks. Findings from the ERGO interviews and literature review highlighted the role of unofficial warning channels. There are limited studies except Hui et al. (2008) on formally incorporating the unofficial warning channel in evacuation warning plan. Moreover, in order for the GOs to test their warning dissemination capabilities and understand the impact of unofficial channels, a simulation model could support the preparedness initiatives. With this intent, this thesis has presented a 'proof of concept' of development and use of a simulation model to plan for warning message dissemination with unofficial channels. The developed model has been illustrated using a case study of ERGO city as introduced in the earlier chapter. The following section presents the details of the ERGO city's evacuation warning details followed by the warning message dissemination model.

4.3.1 ERGO city case study - An overview

This thesis has adopted case study approach to explain the proof of concept on using OR based models for ESF planning. GOs need to understand the uncertainties in household evacuation behaviours for three ESFs and its implication on the success of evacuation. In order to explain the model developed, a hypothetical case called 'ERGO city' is used for illustrating the application of models and how it can help GOs to support their preparedness. It will be used to highlight some of the response strategies that could help the planners to contextualise to their city. Each of the ESF model development chapters (chapters 4, 5 and 6) presents only the respective ESF details of the ERGO city prior to elaborating on the model development and analyses. Section 3.3.5 of this thesis presents the ERGO city demographic details, flood inundation details and the evacuation shelters.

ERGO city case study – Warning message dissemination scenario details

There was a major emergency in the 'flood zone' areas of the ERGO city. The multi-agency committee has decided to evacuate designated areas indicated by blue colour *in the ERGO city map. The flood is expected to breach the dykes within 1.5 hours.*

The decision to evacuate was made considering the safety of the public in view. Police officials in ERGO city are responsible for dissemination the warning message for evacuation. In the warning preparedness section of evacuation plan, they have identified 'TV, radios, mobile messaging, landline message and sirens' as the official channels used for warning the public during evacuation. As a policy, all these channels will be used in tandem to reach out 'everyone in evacuated zones' as 'quickly' as possible.

- Will the people in the designated areas be warned within 1.5 hours prior to the dyke break?
- Will the warning message reach 'everyone' and in a 'timely' manner?

These are some of policy-level questions for this ERGO city context that the emergency responders will be answering as a part of preparedness initiative. Keeping these details about the ERGO city as a context, the following section describes about the model, how various factors of warning plans will affect the warning dissemination, how the warning informant behaviour dynamics of the household with impact overall warning and finally the illustration of simulation approach in supporting warning preparedness for mass evacuation. The same ERGO city will be used for the other two ESFs namely evacuee transport management (Chapter 5) and emergency accommodation planning (Chapter 6).

4.3.2 KPIs for measuring evacuation warning preparedness:

Warning dissemination effectiveness has two dimensions namely 'delivery of the message' and the 'message content'. The design of warning message content was found to be well established underpinning the social science literature (Sorensen and Mileti, 1989). "*An extensive literature existing on how individuals and families interpret and respond to such warnings when they are received"* (Sorensen and Mileti 1987). As the focus of this thesis is on the 'delivery' of the warning message to the evacuating households, the message content and its effectiveness in triggering favourable response from the public though very important is considered to be outside the scope of this thesis.

EMAs use measurable objectives to set operational targets in their response plans for providing timely evacuation warning. For answering the policy-level question on warning preparedness, there are two KPI metrics collected from the model results.

i) '*Expected level of warning*' is defined as the proportion of people who would receive the message under a given condition.

ii) ‘*Notification time*’ is defined as the time required for reaching a maximum proportion of the public (i.e. expected level of warning) under a given condition. Another output metric denotes the distribution of number of sources from which a single household receives the message.

These metrics have been used in earlier evacuation simulation models (Stern and Sinuany-Stern 1989, Rogers and Sorensen 1991, Southworth 1991, Hui et al. 2008) and has been adopted in this thesis. These two metrics are collected and analysed to compare various scenario to know whether the operational targets can be met for a chosen scenario and also the level of warning preparedness. The following section elaborates the model, its development and further experimental result analyses.

4.3.3 Description of warning message dissemination model

Agent-based modelling is widely used in social simulation particularly suitable where behaviour of the entities in a system needs to be modelled. Evacuee behaviour as informants will be modelled using software ‘agents’. The household behaviour of the evacuees like ‘whether they have received the message? and Will they disseminate to their neighbours?’ will be set as properties and behavioural rules for the agents. The warning message model will combine the effectiveness of formal channels along with the informal channels using agent-based modelling in order to measure warning dissemination capability under various conditions. Warning dissemination model contains three aspects of the evacuated area:

i) Evacuation household details and their properties
ii) Official warning channel and their effectiveness
iii) Behavioural rules for unofficial warning dissemination

The ABM canvas contains the evacuated zone, households represented as dots, and evacuation road network represented using arcs. These properties are imported as coordinates into the ABM. A modelled household is represented as an ‘agent’ in the model with members of the household, ‘whether they are present in the house’ and evacuation details (e.g. warning channel available) represented as ‘properties/attributes of agents’ and their ‘behaviours’ (e.g. evacuation decisions) are implemented using rules for agents. Warning system comprises channels used for disseminating the evacuation message including official channels and unofficial channels. The latter is the focus of this thesis. Official warning channels and their respective efficiencies, which are one of the input parameters, are internally represented using time series. Official warning channels such as TV, Sirens, Radio and Telephone have been implemented as channels for disseminating the warning message. The ABM contains logic that disseminates set percent households to receive message from each warning channel.

The purpose of the model is to know the level of warning (% households who received the warning message) for the chosen warning system from the onset of disaster. As the focus of this thesis is to understand 'household warning informant dynamics and its impact on the overall warning dissemination', this behaviour is implemented as conditional rules. For example,

IF a household RECEIVED a warning message
AND decides to IMMEDIATELY EVACUATE
THEN they will NOT warn others.

In the example, a household having received a warning message (state variable/attribute) decides to 'evacuate immediately' (behaviour), which will lead to 'not informing' their neighbours (conditional behaviour). This example rule illustrates how an agent's (household) behaviours are represented as a function of its state variable, behaviours and conditional behaviours in a simple conditional rule (IF-THEN). As the evacuated zone will have number of houses (agents), with varied evacuation warning behaviour (micro-behaviour) and the interaction among households (agents) will impact overall ET (macro-behaviour). The 'informant behaviour' of the evacuees will require modelling the behaviour of the individual units (namely household and moving vehicle), its behaviour dynamics, the interaction among the individual units and its implication on the overall system. Agent-based Modelling technique's features offer a suitable fit for behavioural simulation, and this has been adopted in designing the warning dissemination model.

4.3.3.1 Model development phases

For the GOs to use 'informal warning channel' within their warning dissemination plan, it is first important to understand what choices are made at a household level at the warning phase? Once a generalisable logic (considering various alternative choices) is presented for one house, then this can be scaled up to a region of a city or a city. As modelling a complex problem like large-scale evacuation requires accurate representation of modelling logic, very large-scale units to be modelled and numerous inter-related behaviours, this thesis has adopted prototyping for developing the model.

In phase-1, a hypothetical community of neighbourhood with 1000 households in an equally spaced rectangular grid of 50 x 20 is modelled as a prototype. The logic of 'household behaviour' as informal warning channel was formulated, implemented as a software code in the prototype and tested. Readers are referred to Nagarajan et al. (2010, 2012) for more information on the prototype warning dissemination model. Such prototyping offers a controlled modelling environment that can be sequentially enhanced to contain additional features of interest in the subsequent model iteration. This prototype was experimented to understand the household informant behaviour dynamics through sensitivity analyses and simulation experiments.

Once a validated and verified logic of household behaviour is programmed for a small community, phase 2 of the model implemented the warning dissemination at a city scale with details of the households in the ERGO city, access to various warning channels and EMA's warning system capability. The following section presents phase 1 of the ABM development, experimentation of ABM and findings. Section 4.5 of this chapter presents the ABM for the ERGO city.

4.3.3.2 Structure of ABM for a hypothetical community

The ABM, which was developed using NetLogo software for a hypothetical community of 1000 houses, incorporates one official channel along with the unofficial channel. There are other ABM platforms namely Repast Simphony, MASON, StarLogo, etc (Macal and North 2009, p 94). Given the ease of use for the non-IT savvy emergency managers and customizable inbuilt functions, NetLogo is more appropriate. When the geographical coordinates of the city are available from GPS systems and when the evacuation zone details and impacted area are available as GIS layers, the evacuation city features can be imported into the model canvas as layers more easily in Repast Simphony software. However, for illustrating the proposed methodology, GIS maps of ERGO city data was available as point data and not in any standard GIS image formats linked with database. For importing evacuation zone data as 'formatted' coordinate files, NetLogo's inbuilt features are reasonably powerful enough to build the model area during run-time the ABM.

The ABM setup routine has been designed to customise it for any other city with a formatted coordinate data file. The disadvantage of NetLogo is that it has a limited flexibility in generating output graphs interactively by the user, and this has been handled by writing 'standard output reports' as a sub-routine. The problem under study could be modelled using excel spreadsheet, DES software or any other programming language. Any ABM software provides 'building blocks' for setting household level (agent) behaviours and interactions, which makes the model development considerably less effort.

The model is of a hypothetical community of 1000 households represented as a rectangular grid. All the houses are assumed to be occupied at the time of warning dissemination. The unit of analysis is the individual household, which is modelled as agents. Each agent has attributes such as: identification number, media channels available (e.g. TV, radio, etc), 'defaulter variable' (are they willing to communicate the message, or not) and state variable (informed, uninformed, disbelief).

As presented in the literature review, warning dissemination has two phases namely warning and informing. Warning phase deals from the onset of evacuation warning till the household receiving the message. This phase pertains to the ability of the warning system (all the means of disseminating message – channels) to alert a household of the emergency situation. The informing phase considers how long it takes for the recipients to interpret the message. Warning capability is an aggregate function of the effectiveness of the channels in the warning system to reach households in the endangered zone. The response of a household to an evacuation message is a function of their threat perception, preparedness and believability of warning message. The warning message content plays a key role in influencing the response, and there has been considerable research already done in this field; this thesis focuses on successful delivery of the warning message only.

4.3.3.3 Household agent's unofficial warning behaviour

The behaviour of households as informants to neighbours has various dimensions (Figure 4.1). When the household receives a warning message, they move from an 'uninformed' to an 'informed' state. The public require time from receiving the warning message to doing something about it (responding) as it takes time to assimilate/understand/verify the message content. This time henceforth is called as 'assimilation time' (t_b) as adopted by Rogers and

Sorensen (1991). In a post-evacuation survey by Balluz et al. (2000), 45.7% of people responded to a tornado warning, of which 90.6% took action within 5 minutes. There is uncertainty in this factor as some proportions of the public assimilate the warning message immediately while others take a longer time. As there was little published data on this factor, the uncertainty of the parameter t_b has been tested in this thesis using sensitivity analysis on the mean value, the variation, and the statistical distribution of t_b. The model considers the delay for the people to begin informing the neighbours 't_b' as first input parameter for the model.

A non-defaulter household, after the assimilation time (t_b), would begin informing neighbours. The selection set of the neighbours around the house is modelled in this study as 'selection policy'. There are four different policies considered in this study namely:

i) informing an adjacent house only,
ii) informing an adjacent and opposite house,
iii) informing four neighbours i.e. one in each compass direction,
iv) informing between 1 and 4 houses (X) as represented as a discrete uniform distribution namely X = {1, 2, 3, 4}; the respective probabilities are given by p(X=x) = {0.25, 0.25, 0.25, 0.25}.

These four selection policies allow modelling the uncertainty in the neighbour selection set and the implication of this on the overall warning level. This behaviour will be studied using ABM and will enable the warning policy planners to know the relative impact on warning dissemination. The simple wording of selection policy enables easier communication to the general public to persuade them in informing their neighbours. 'Selection policy' is the third parameter for household warning behaviour in the ABM.

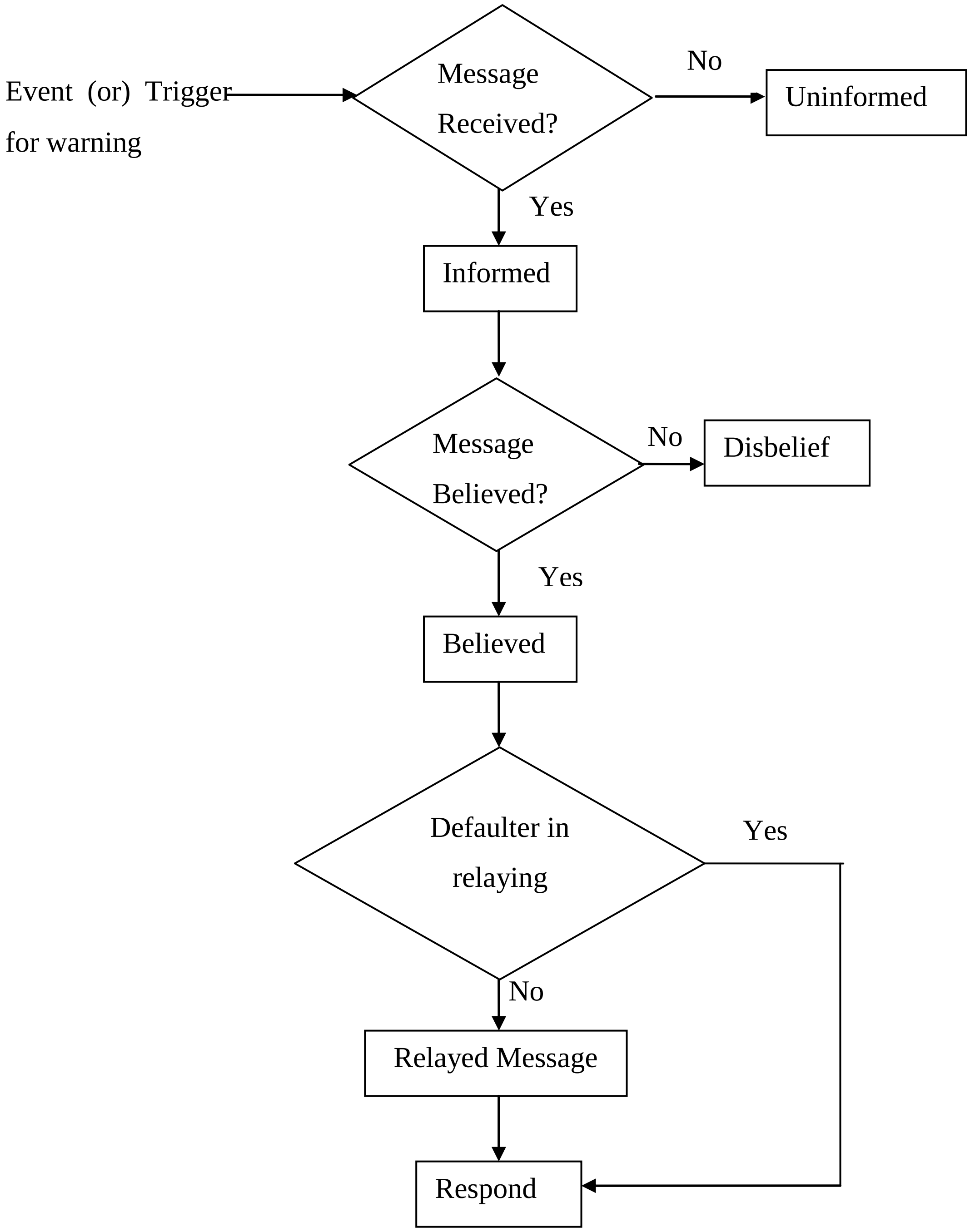


Figure 4.1 Various states of the public in receiving the warning message (based on Rogers and Sorensen, 1991, p120)

Once the household has received the warning message and after a time lapse of t_b minutes, the non-defaulter household inform a set of neighbours depending on any of the four selection policies discussed above. The time required to leave their house, reach a neighbour, and inform them about the warning message along with directing them to official source (if any) and then returning to their own house, is henceforth called as 'time to inform' (denoted by t_i). This uncertainty in the 'time to inform' is due to various factors, e.g. the variation in the distance to be travelled, duration of actual conversation and time to comprehend the urgency of the warning message. 't_i' is the fourth parameter for representing household informant behaviour in the warning dissemination model. This thesis has studied the uncertainty of t_i using sensitivity analysis over a range of values, namely t_i=2 to t_i=10 minutes.

Official messages that inform the public often request recipients to relay the message to neighbours and friends, e.g. the Red Cross (2005). However, not all households that receive the message will relay this message to their neighbours (Kreps 1984) – perhaps because they perceived urgency for themselves, leading to immediate evacuation and hence not warning the neighbours. These households are categorised as 'defaulters'. Thus, two variables are needed to take account of the uncertainty in the proportion of people who warn their neighbours (P_w), and the uncertainty in the proportion of people who do not warn their neighbours (P_d) i.e. defaulters, where $P_d = 1–P_w$. 'P_d' is the second input parameter for household behaviour.

On estimates for these variables, a survey by Parker et al. (2009, p106) reported that "*22% of the respondents informed their neighbours, 16% telephoned other family members, 39.9% warned other household members, and the remainder did not pass the information*". Two studies reported in Parker and Handmer (1998, p55) found that the proportion of people who warned their neighbours (P_w) was found to be 22% and 40% – suggesting that the P_d could vary between 60% (100%–40%) and 88% (100%–22%). The value of P_w will depend on the cohesion among the households within a community and could be different for different cultures; thus P_w=0.32 and P_d=0.68 are taken as values to represent the probability of warning/defaulting on disseminating the warning message. However, due to the uncertainty of P_d, its effect on overall warning level is studied using sensitivity analysis for a broader range of 20% to 90%, representing more cohesive societies to less cohesive societies, respectively.

The unofficial source is modelled along with the four selection policies. The effectiveness of warning message dissemination will be measured using the KPIs presented in section 4.3.2. Table 4.3 maps the features of the ABM and the components in the warning dissemination model. Depending on whether a household is a defaulter or not, the timeline from evacuation order to evacuation (leaving the house) varies. The above figures present the timeline diagrams for a defaulter (Figure 4.2) and a non-defaulter house (Figure 4.3).

Table 4.3 ABM features mapping with Warning dissemination problem

ABM Feature	Informal dissemination
Agent	Household
Agent behaviour	Inform about the evacuation warning message to the neighbour
Agent attribute	Whether they will inform neighbours or not
Decision	On receiving the message and after understanding it, inform a set of neighbours.
Interaction among agents	Household-to-household warning communication
Overall emergence	Impact of the informal channel on the overall warning dissemination

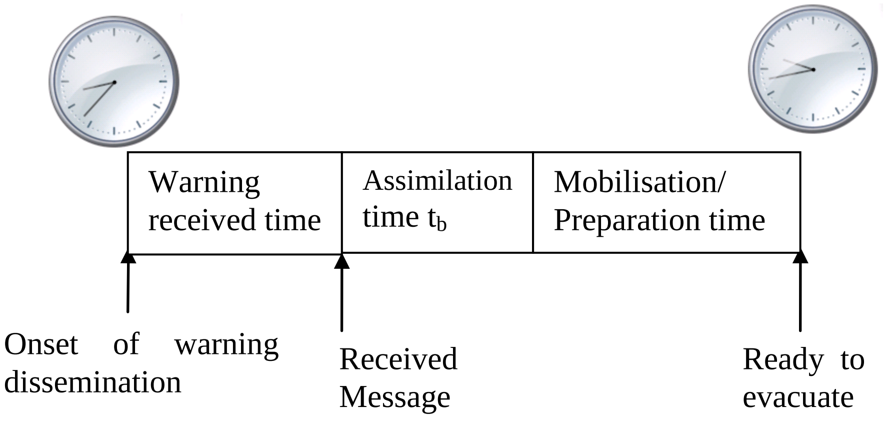


Figure 4.2 'Warning to evacuation' timeline for a defaulter household

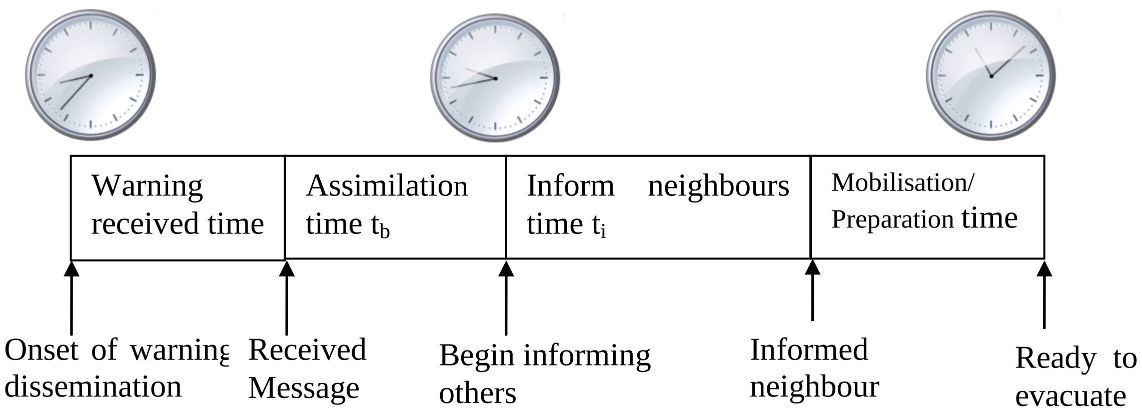


Figure 4.3 'Warning to evacuation' timeline for a non-defaulter house

EMAs during their preparation stage could understand the warning capability and means of improving it by detailed understanding of the timeline at a household level. Warning time, the time when a house receives the message, depends on the warning system capability and also the access to official channels at the household. This time will possibly be reduced due to the presence of unofficial channels. For a household informing their neighbours, their selection policy (number of neighbours to inform) will influence the total time needed for informing. By having the warning message clear and directing the neighbours to the warning message than elaborately explaining, this total time could be reduced at a household level. Keeping the 'warning received time' as a constant for defaulter and non-defaulter houses, the time when they will be ready to evacuate will be longer for houses informing their neighbours. However, the overall 'warning received time' (notification time) could possibly be reduced by encouraging households to inform their neighbours, and the prototype ABM developed in thesis will be experimented to measure the level of improvement in the notification time at the individual vs. community level.

4.3.3.4 Implementation of household (agent) warning informant behaviour

The input parameters for household warning informant behaviour (unofficial warning channel) has been summarised in Table 4.4. These parameters are entered in the NetLogo user screen at the setup stage prior to execution. As a first step in ABM, the household location details and its properties (e.g. access to warning channel, family size, etc) are to be loaded as agents and its attributes. A screenshot of the model is as shown in Figure 4.4. A household-property file is a comma-separated formatted input file created for the hypothetical community and loaded in the setup stage. Each row in this file represents one household and the ABM creates an agent on the specified coordinate and assigns initial properties to the house. All the houses are flagged as 'not warned' at the time of loading. After loading the evacuation area, the input parameters set on the screen are loaded along with the official channel effectiveness.

Table 4.4 ABM Warning dissemination model parameters

Parameter Type	Parameter	Description
Input	Assimilation time (t_b) in minutes	Time to understand and react to the warning message
Input	Defaulter % (P_d)	Percentage of people who will NOT inform neighbours
Input	Neighbour selection policy	Number of neighbours that a person will visit to inform
Input	Time to inform neighbour (t_i)	Time taken to visit each neighbour and inform them
Output	Level of warning (%)	Percentage of the population that has received the message
Output	Notification time (minutes)	Time taken to reach a saturation point in the level of warning

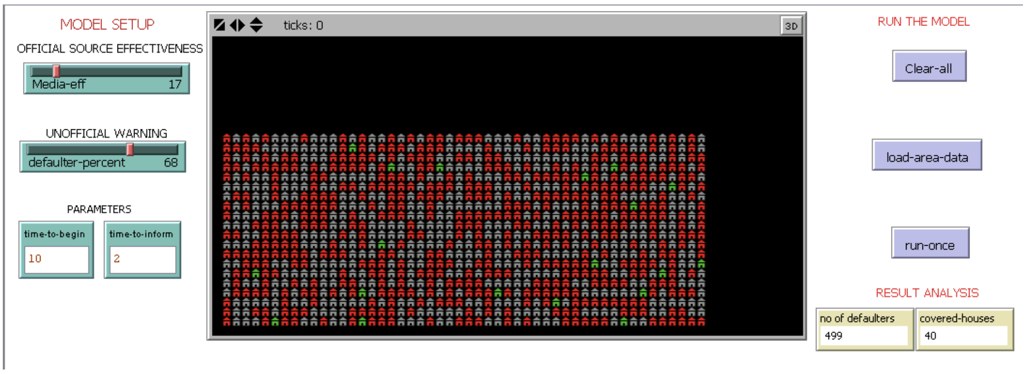


Figure 4.4 Snapshot of ABM warning dissemination model – prototype

```
;; set-defaulter-houses procedure randomly selects the pre-specified % of houses
;; as being defaulter in relaying the emergency message to neighbours
to set-defaulter-houses
    repeat (defaulter-percent * no-of-houses / 100)
      [ ask house (random (no-of-houses - 1) )
        [ set defaulter-flag true
        ]
      ]
End
```

Figure 4.5 Code snippets for 'defaulter houses' selection sub-routine

Based on the value of P_d, a random set of houses among the households are set as 'defaulters'. The code snippet provided below presents the random selection of defaulter houses (Figure

4.5). When the evacuation advice dissemination begins, all the houses remain uninformed. When the simulation clock is at every 10 ticks (10 minutes), the percentage of coverage for the official channel is used to selected houses randomly to have received the initial warning message (initial seeds) as given in the code snippet lines 11 to 20 as presented in Figure 4.6. When there is more than one official channel, initial seeds are selected in each cycle for every official channel. This official channel cycle is executed every 10 minutes and incremental percentage covered is used to know how many houses will receive the warning message in a particular cycle. For example a siren has effectiveness of {10%, 25%, 70%} for time {10, 20, 30} minutes, then at the time t = {10, 20, 30} the 'official channel cycle' sub-routine will randomly select {10%, 15%, 45%} houses to be warned. It must be noted that a house that was warned in one cycle could also be selected by random choice for warning, but the first warning message is set as 'warning received time'. The initial seed selection has been presented in the code snippet lines 22 to 56 as presented in Figure 4.7.

```
11 to set-initial-seed
12     let proc-name "set-initial-seed"
13     show (word "Begin: " proc-name)
14     '' official-channel-cycle  1 "A" ;; siren
15     '' official-channel-cycle  1 "B" ;; tone-alert
16     '' official-channel-cycle  1 "C" ;; media
17     official-channel-cycle  1 "D" ;; telephone
18     show (word "End: " proc-name)
19 end
20
```

Figure 4.6 Code snippets for 'initial seeds' selection sub-routine

```
22 to official-channel-cycle [cycle chnl-cd]
23   let proc-name "official-channel-cycle "
24   show (word proc-name cycle " " chnl-cd  )
25   let chnl-eff 0
26   let i 0
27   if (cycle = 1)[
28     if (chnl-cd = "A") [ set chnl-eff (item cycle siren-eff-list)]
29     if (chnl-cd = "B") [ set chnl-eff (item cycle tone-alert-eff-list) ]
30     if (chnl-cd = "C") [ set chnl-eff (item cycle media-eff-list) ]
31     if (chnl-cd = "D") [ set chnl-eff (item cycle telephone-eff-list) ]
32   ]
33   ;; Incremental no of new houses will be selected.
34   if (cycle >= 2)[
35     if (chnl-cd = "A") [ set chnl-eff ( (item cycle siren-eff-list) - (item (cycle - 1) siren-eff-list) )]
36     if (chnl-cd = "B") [ set chnl-eff ( (item cycle tone-alert-eff-list) - (item (cycle - 1) tone-alert-eff-list) )]
37     if (chnl-cd = "C") [ set chnl-eff ( (item cycle media-eff-list) - (item (cycle - 1) media-eff-list) )]
38     if (chnl-cd = "D") [ set chnl-eff ( (item cycle telephone-eff-list) - (item (cycle - 1) telephone-eff-list) )]
39   ]
40   if (chnl-eff >= 0 )[
41         repeat (chnl-eff * no-of-houses / 100) [set i (random (no-of-houses - 1) )
42                                                ask house i
43                                                    [
44                                                    set color green
45                                                    set recd-msg true
46                                                    ;;set source-count (source-count + 1)
47                                                    off-source-duplicate-count i chnl-cd
48                                                    if (recd-time = 0) [
49                                                          set recd-time ticks
50                                                          set neigh-inform-time (ticks + time-to-begin )
51                                                    ] ;; set only the first msg.
52                                                    ]
53                                          ]
54       ]
55 end
56
```

Figure 4.7 Code snippet for official warning channel – intial seed selection.

The focus of this thesis is to model the unofficial warning dissemination to neighbours as a warning channel. Non-defaulter houses that received the warning message and have assimilated the message are considered to be ready for warning their neighbours. A list of household ids ‘ready to inform others’ is generated in every tick as a first step in the unofficial warning channel, and this has been presented in the code snippet in Figure 4.8.

```
'' creates a list of houses that have already received warning message and ready to inform neighbours.
'' The list includes potential seeds for relaying message in the present cycle - Hence excludes defaulters,
'' houses who ;; have already informed their neighbours and also houses who have completed warning assimilation period
to houses-informed
  let proc-name "houses-informed"
  'show (word "Begin: " proc-name)
  set houses-avail-to-inform-list []
  foreach sort houses
  [
  ask ? [

        if (  ( [defaulter-flag] of ? != true ) AND ( [recd-msg] of ? = true ) AND
              ( [inform-neigh-flag] of ? != true ) AND ( [neigh-inform-time] of ? <= ticks)  )
            [set houses-avail-to-inform-list lput who houses-avail-to-inform-list]
        ]
  ]
  'show (word "End: " proc-name)
end
```

Figure 4.8 Code snippet for selecting new houses ready to inform neighbours at t = tick

The time between warning onset and disaster strike will have a role on whether a household will inform neighbours or not. The time to disaster strike and its implication on defaulters has not been modelled in this thesis. For the houses ready to inform their neighbours, a neighbour selection policy is set at the household level and they warn the neighbours sequentially. If the neighbour has not received the warning message, then warning time is set for those houses. Depending on the number of neighbours chosen, the total time needed for the house to inform their neighbours is a multiple of t_i (time to inform). This time is set for the household serving as an unofficial source and will not be selected for subsequent warning in the next cycles. The sub-routine for implementing unofficial channel in the ABM has been presented as a code snippet in Figure 4.9.

```
to inform-neighbour
  let proc-name "inform-neighbour"
  houses-informed
  ;; show (word proc-name houses-avail-to-inform-list)
  let i 0
  let j 0 '' j is a variable that accounts for diff in time of recev message among neigh houses.
          ''This could be changed into random function in future.
  let h 0 '' h is an index variable to move among neigh
  let clr 0
  set clr (random 139)

  ;; official source countinuous every 10 minutes.
   If ( (ticks < 90 ) AND ((ticks mod 10) = 0) )
   [
         official-channel-cycle ((ticks / 10) + 2 ) "D"
   ]

  ; Unofficial source dissem - begin
  foreach houses-avail-to-inform-list
  [
    set i ?
    set j 0
     ask house i [
     '' ALL FOUR NEIGHBOURS
     ask houses-on (n-of ( (no-of-neighbours) + 1) neighbors4) [
             set j (j + time-to-inform)
             ;; if (i = 90) [ show j]
             set color green
             if (recd-time = 0) [set recd-time (ticks + j)        set neigh-inform-time ((ticks + j) + time-to-begin)]
             set recd-msg true
             ;; set source-count (source-count + 1) ;; added on 30-Nov
             if ((position i source-cd-list) = false)[                  ;; added on 30-Nov
                 set source-cd-list lput i source-cd-list
                 set recd-time-list lput ticks recd-time-list
                 set source-count (source-count + 1)
                    ]
             ]
      set inform-neigh-flag true
           ]
  ]

  update-results
  do-plots
  |
  '' Unofficial source dissem - end
  tick-advance 1

  '' end of informing
  reset-defaulter-color

'' check-saturation-point
    if (saturation-count >= (3 * time-to-begin) )
        [stop]
end
```

Figure 4.9 Code snippet for agent behaviour: unofficial warning channel

4.3.3.5 Simulation experiment design for uncertainty in household informant behaviour

The household informant behaviour is represented using four input parameters. The value for each of these parameters is uncertain for a household. The uncertainty in the input factors has been investigated here using 10 scenarios (Table 4.5). The analysis found that 100 replications of the model is sufficient to obtain stable output results without bias from (a) the initial selection of which houses receive the warning message and (b) the uncertainty of any of the four selection policies for a specific scenario.

Table 4.5 Various scenarios for behavioural assumption of the public as an unofficial source

Scenario	**Unofficial source**	**Assimilation time (t_b)**
Scenario – A	No	Not applicable
Scenario – B	Adjacent neighbours	Deterministic (10 min)
Scenario – C	Adjacent and Opposite	Deterministic (10 min)
Scenario – D	All four neighbours	Deterministic (10 min)
Scenario – E	Number of neighbours (X) to be informed is chosen using discrete uniform distribution. X = {1, 2, 3, 4} p(X=x) = {0.25, 0.25, 0.25, 0.25}	Deterministic (10 min)
Scenario – F	Adjacent neighbours	Normal distribution (t_b = 10min, σ_{tb}= 4min)
Scenario – G	Adjacent and Opposite	Normal distribution (t_b = 10min, σ_{tb}= 4min)
Scenario – H	All four neighbours	Normal distribution (t_b = 10min, σ_{tb}= 4min)
Scenario – I	Number of neighbours (X) to be informed is chosen using discrete uniform distribution. X = {1, 2, 3, 4} p(X=x) = {0.25, 0.25, 0.25, 0.25}	Normal distribution (t_b = 10min, σ_{tb}= 4min)
Scenario – J	Number of neighbours (X) to be informed is chosen using discrete uniform distribution. X = {1, 2, 3, 4} p(X=x) = {0.25, 0.25, 0.25, 0.25}	Deterministic t_b = 10 min Stochastic t_i = 2min and σ_{ti} = 1min

Scenario – A represents the scenario where only official channel is available for warning dissemination. Based on the official channel effectiveness, a new set of houses are randomly selected every 10 minutes as though 'receiving warning message'. As the unofficial channel is absent in this scenario, the household receives the warning message and respond to evacuation. For other scenarios (B – J) with unofficial channel, the official channel dissemination is similar to 'Scenario – A', i.e. a new set of houses are selected every 10 minutes and these houses will be available for informing their neighbours after a time delay of t_b. If the house has received the warning for the first time, then the house will be available as unofficial channel. Depending on the defaulter attribute of the house, selection policy of neighbours, the household will act as informal channel as presented in Figure 4.1.

To determine the 'run-time' of the model (defined as the number of time units/minutes the model is run), the warning message dissemination model was executed for various 'stopping criteria'. The stopping criterion (t_s) is defined as the number of time units beyond which there is no subsequent dissemination of warning message among neighbours (warning level saturation). In other words, the number of houses informed at time $t = (t_n + t_s)$ is equal to the number of houses informed at time $t = t_n$. The time ($t = t_n$) where the warning level attains saturation is nothing but the warning 'notification time'. The run-time of the model would have an impact on the 'level of warning'; hence this variable is chosen to compare various stopping criteria. For each run, the output results, namely mean and standard deviation (Std), were collected corresponding to stopping criterion t_s = {5, 10, 20, 30 and 40 minutes} and tabulated in

Table 4.6. It was found that the stopping criterion of 20 minutes is enough to obtain consistent results.

Table 4.6 Simulation results for various stopping criteria for Scenario E

KPI	**t_s = 5min**		**t_s = 10 min**		**t_s = 20 min**		**t_s = 30 min**		**t_s = 40 min**	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Level of warning (%)	9.55	0.2	83.2	1.52	83.08	1.8	83.08	1.5	83.34	1.6
Notification time (in min)	0	0	104.6	9.84	109.10	14.6	109.96	13.7	109.72	13.4

4.3.3.6 Impact of unofficial warning channel estimated using simulation experiments

The ABM prototype model was adapted to run each Scenario A-J. There are four input parameters used in the model, and the representative values were used for the base scenario (Scenario A). The uncertainty of the number of houses informed was represented as different behavioural policies (Scenario E to I). The approach used in developing the model is generalisable, and upon the availability of more reliable data the users can input this at the setup stage. The input parameters provided at the setup stage are:

- 'Assimilation time' t_b = 10 minutes, which is the amount of time it takes for a household to understand the warning message and decide how to respond.
- 'Proportion of defaulter' P_d = 68%, which is the likelihood of a household not passing the warning message on to its neighbours.
- 'Time to inform the neighbour' t_i = 2 minutes, which is the amount of time it takes a household to go and tell its neighbour(s) and return to the household.

The model is replicated 100 times with stopping criteria of 20 minutes to obtain the KPIs level of warning and notification time. Table 4.7 summarises the results of simulation for the Scenarios A to J. Scenario A is the base scenario of having an official warning channel, no unofficial channel and a deterministic value for assimilation time t_b. Comparing this to the other deterministic scenarios (B to E), results from running the model show that the highest difference in the warning level from the base Scenario A (51.4%) was for Scenario D (95%), an increase of 43.6% from the base scenario. For the stochastic scenarios, the warning level for the base scenario was Scenario E (83.2%) with the highest difference in the warning level for Scenario H (95.1%), an increase of 11.7% from the base scenario. The variation on the notification time from the base Scenario A (91 minutes) is found to be similar for all other Scenarios (B to I) with an average of 110.5 minutes and the highest for Scenario J (131 min). This suggests that the strategy for the unofficial warning dissemination to neighbours could have considerable impact on the overall warning level for the population. Hence, it might be suggested that GOs could influence dissemination by educating the public in advance on the merits of sharing the warning message as well as including instructions to do so in any official warning and informing messages during an evacuation.

The range of variation in the level of warning is shorter in the scenarios with stochastic t_b values than deterministic t_b values. Scenario E (uniform distribution of number of neighbours informed per household) has an expected warning level between the pessimistic scenario

(Scenario B) and the optimistic scenario (Scenario D) of the effect of unofficial warning dissemination on the overall effectiveness. Scenario E takes longer for the notification time to reach the expected level of warning. Thus, Scenario E can be considered as moderate scenario for accounting the behaviour of public as unofficial source.

The uncertainty in the behaviour of potential defaulters in informing the neighbour is studied using sensitivity analysis by varying the 'likelihood to be defaulter' P_d value from 20% to 90% in steps of 10%. The number of neighbours informed per household is taken as discrete uniform distribution (Scenario E) with t_b = 10 minutes. With all the other factors remaining constant, it was found that for every 10% increase in likelihood of defaulters (lowering the level of unofficial warning), the expected level of warning decreases by approximately 2.62%.

Emergency managers have situations where they have specific operational target time set for warning dissemination. For example, if the government agency forecasts that a tsunami wave will hit in 90 minutes, the warning authorities may find it useful to know the percentage of population who can be warned. Considering 90 minutes as a cut-off point, the ABM was run once for different scenarios with the input parameters t_b = 10 minutes, t_i = 2 minutes, P_d = 68%. Figure 4.10 shows the comparison of the warning level from the onset of dissemination for different scenarios listed in Table 4.5. For example, it can be observed that, at the end of the 90 minutes, the warning level is within the range 52% (Scenario A) to 95% (Scenario H).

Among the scenarios including the unofficial warning channel, the lowest warning level is about 78% (Scenario F), which infers that the warning level will be underestimated by 26% (Scenario A) due to excluding the unofficial warning channel. For the emergency managers the warning level can be expected to increase at least by 26% by encouraging people to warn their neighbours irrespective of their neighbour selection behaviour.

The comparative analyses show that there is pair-wise similarity among the scenarios with the same neighbour selection policies namely: Scenarios B and F (adjacent neighbours), Scenarios C and G (adjacent and opposite) and Scenarios D and H (All four neighbours). The impact of uncertainty of t_b is more prominent between Scenarios E and I, where the warning level difference is about 7% (89% - 82%). Similarly, the impact of uncertainty in t_i is about 7% (89% - 82%) between Scenario E and Scenario J.

Table 4.8 summarises the results for various values of likelihood of defaulting (P_d) for Scenario E. Experiments tested the defaulter parameter from 20% to 90% and results suggest that the parameter is sensitive in affecting the level of warning (range 95.6-77.6% when the defaulter parameter increases from 20% to 90%). However, the defaulter parameter does not have considerable impact on the corresponding notification time (range 106.7 minutes to 108.4 minutes for these experiments).

Table 4.7 Results on varying the unofficial warning channel and varying t_b

Performance metric	Scenario																			
	A		B		C		D		E		F		G		H		I		J	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Level of warning (%)	51.4	0.8	78.6	1.6	90.2	1.2	95.0	0.8	83.4	1.6	78.6	1.5	90.2	1.2	95.1	0.9	83.2	1.5	4	1.5
Notification time (minutes)	91.0	0	111.6	14.3	109.9	16.8	105.2	14.3	110.3	15.0	111.5	12.2	111.3	14.8	112.4	18.6	112.1	13.3	131	11.8

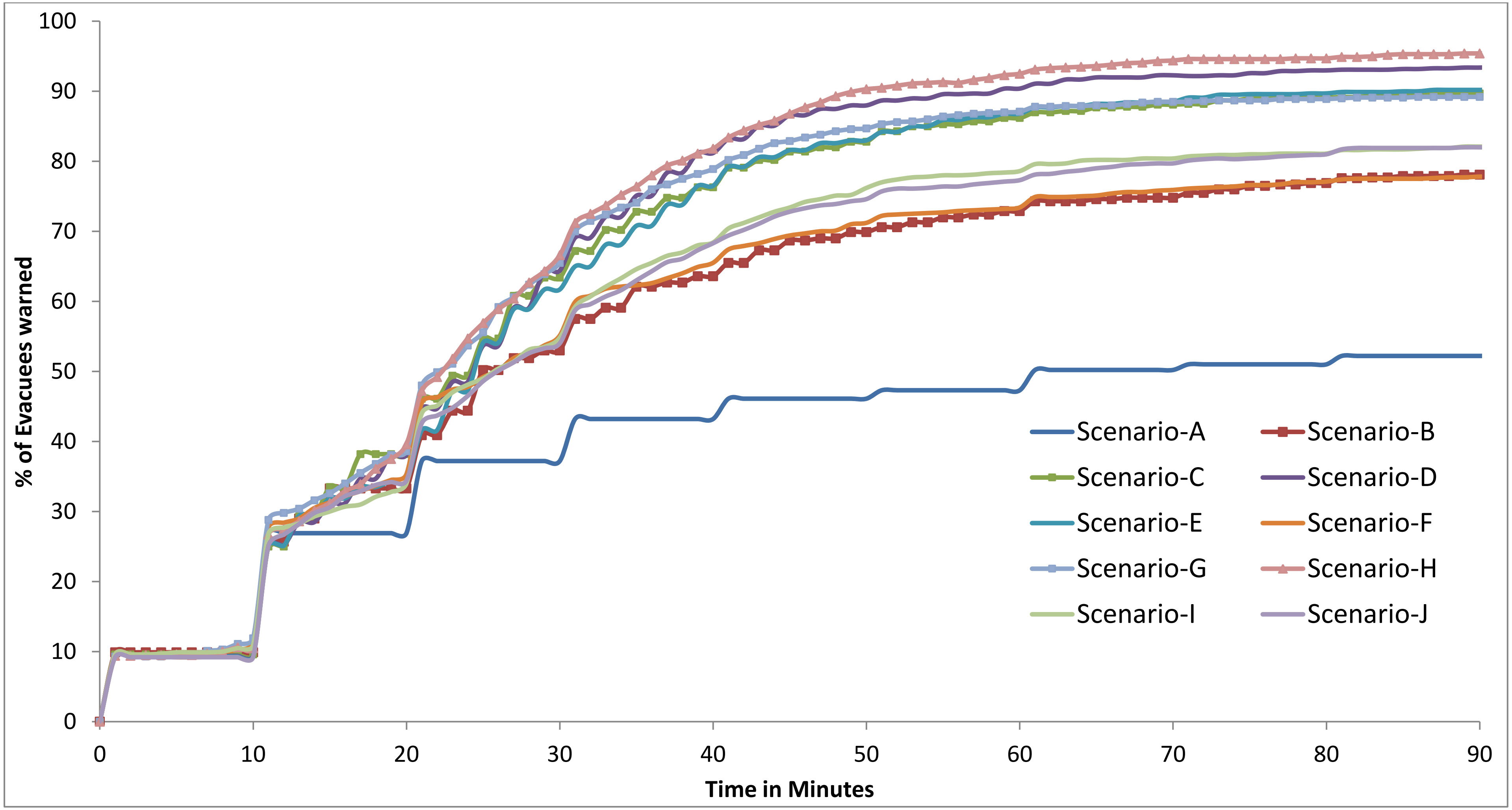


Figure 4.10 Comparison of the changes in the 'warning level'

Table 4.8 Sensitivity analysis of P_d (defaulter) on warning dissemination for scenario E

Performance metric	P_d = 20 %		P_d = 40 %		P_d = 50%		P_d = 60%		P_d = 70%		P_d = 80%		P_d = 90%	
	Mean	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**
Defaulter houses (%)	18.1	0.4	33.0	0.6	39.4	0.8	45.2	0.7	50.3	0.9	55.0	0.9	59.3	1.0
Level of warning (%)	95.6	0.9	91.0	1.2	88.4	1.3	85.6	1.5	83.0	1.8	80.3	1.7	77.6	1.6
Notification time (mins)	106.7	12.8	108.0	11.6	110.7	12.7	111.1	13	110.6	13.5	109.9	14.3	108.4	12.8

i) Uncertainty in the assimilation time (t_b)

On receiving the warning message, each household would require time of t_b to assimilate the information they have received and make a decision on how to respond to that. The uncertainty of the value of t_b has been studied by conducting sensitivity analysis on various aspects namely

i) the average value of t_b in the range 5-30 minutes,
ii) variation in the value of t_b represented using standard deviation of t_b in the range 2-8 minutes,
iii) the 'time to begin factor' represented using various statistical distribution (normal, exponential, Poisson and gamma).

The results of model experiments namely warning level (WL) and notification time (NT) are summarised using mean and standard deviation. The experiments on the three uncertainties in t_b are given in Table 4.9, Table 4.10, and Table 4.11 respectively.

Table 4.9 Sensitivity analysis of t_b (delay time) on warning dissemination for Scenario E

KPI	t_b = 5min		t_b = 10 min		t_b = 15 min		t_b = 20 min		t_b = 25min		t_b = 30min	
	Mean	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**
WT (%)	83.0	1.6	83.4	1.7	83.2	1.7	83.4	1.6	83.4	1.6	83.2	1.5
NT (mins)	93.8	9.2	109.4	13.8	131.8	18.7	150.3	22.8	174.9	24	199.5	26.9

Results in Table 4.9 show that the assimilation time does not have a considerable impact on the overall level of warning in the model, but the overall notification time increases due to the longer delay time in assimilation. From Table 4.9, for every 5 minutes increase in the value of t_b, the expected notification time increases in the range of 15.5 minutes to 24.5 minutes. The expected notification time almost doubles (from 93.8 minutes to 174.9 minutes) when the value of t_b increases fivefold (from t_b = 5 minutes to t_b = 25 minutes). Thus, the assimilation time can have a considerable impact on the overall notification time – far beyond the added time that it takes to assimilate the information.

The uncertainty in the value of the assimilation time is represented using the standard deviation σ_{tb}. Table 4.10 summarises that for the same average value of t_b, with uncertainty in σtb (2 minutes to 8 minutes) the value of expected notification time changes by 6 minutes (from 109 minutes to 116 minutes). Thus, the variation in t_b (σ_{tb}) is less sensitive and has considerably less impact on the overall notification time and no impact on the level of warning.

Table 4.10 Sensitivity analysis of the standard deviation of the assimilation time (t_b) for Scenario I

Performance metric	t_b = 10min, σ_{tb} =2 min		t_b = 10min, σ_{tb} =4 min		t_b = 10min, σ_{tb} =6 min		t_b = 10min, σ_{tb} =8 min	
	Mean	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**
Level of warning (%)	83.5	1.7	83.5	1.4	83.5	1.6	83.3	1.7
Notification time (in min)	109.5	13.2	112.0	16.3	115.5	14.1	115.8	13.9

The uncertainty in the distribution of the assimilation time factor was studied with four distributions (normal, exponential, Poisson and gamma). The uncertainty in distribution of t_b will influence when evacuees begin to inform their neighbours and not whether they will inform or not. Hence, this uncertainty will only have an impact on the expected notification time and not on the expected warning level. The expected assimilation time was found to be pessimistic when using an exponential distribution.

Results in Table 4.11 show that none of the other three distributions had a significant impact on the overall expected notification time with a highest variance of 3.5 minutes (between the deterministic and the gamma distributions). Thus, it was found that the normal distribution for t_b had a moderate effect on the overall effectiveness of warning message dissemination (as expected). But, for the purposes of planning aiming to prepare for the worst-case scenario, adopting exponential distribution would provide a more pessimistic estimate (i.e. a longer time to assimilate the warning message).

Table 4.11 Results for different statistical distributions of assimilation time (t_b = 10 minutes σ_{td}= 4minutes)

Performance metric	t_b as Deterministic uniform distribution		t_b as Normal distribution		t_b as Exponential distribution		t_b as Poisson distribution		t_b as Gamma distribution	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Level of warning (%)	83.4	1.6	83.2	1.5	83.3	1.6	83.2	1.6	83.2	1.8
Notification time (in min)	110.3	15.0	112.2	13.3	125.4	16.8	111.3	13.9	114.0	13.3

ii) Uncertainty in time to inform each neighbour t_i

The uncertainty in the factor t_i (i.e. the time required to leave the household, inform the neighbour(s) and return to the household) was studied for a range of values between 2 and 10 minutes, and the results are presented in Table 4.12. This factor will have an impact on the overall notification time as the error in t_i will delay the informing of subsequent neighbours, but this should not have an impact on the overall level of warning. Results in Table 4.12 show that for every 2 minutes increase in t_i, the expected notification time increases by an average of 12 minutes. Thus, the longer the time to inform each neighbour (either due to travel between household to neighbours or due to actually conveying the message), the disproportionately higher will be the overall expected notification time.

Table 4.12 Sensitivity analysis of t_i (time to inform) for Scenario E

Performance metric	t_i = 2 mins		t_i = 4 mins		t_i = 6 mins		t_i = 8 mins		t_i = 10 mins	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Level of warning (%)	83.3	1.5	83.4	1.7	83.4	1.6	83.5	1.4	83.3	1.6
Notification time (in min)	108.6	13.7	121.9	18.0	134.8	19.8	146.4	19.4	162.8	23.6

The uncertainty in the distribution of the 'time to inform' factor was studied with four distributions (normal, exponential, Poisson and gamma). This uncertainty will influence the 'time when evacuees leave to inform their neighbours' whether or not they will inform or otherwise. Hence, this will only have an impact on the expected notification time and not on the expected warning level. The expected 'time to inform' was found to be pessimistic when using a 'gamma distribution' compared to the deterministic scenario (132.9 – 121.9 minutes). Results in Table 4.13 show that all the four distributions had almost similar impact on the overall expected notification time (average 131.8 minutes) with a highest difference of 11 minutes (between the deterministic and the gamma distributions).

Thus, it was found that among the three distributions (normal, exponential, and Poisson), the normal distribution for t_i had a moderate effect on the overall effectiveness of warning message dissemination (as expected). But, for the purposes of planning aiming to prepare for the worst-case scenario, adopting 'gamma distribution' would provide a more pessimistic estimate (i.e. a longer time to inform the neighbours).

Table 4.13 Results for different statistical distributions of 'time to inform' (t_b = 10 minutes t_i = 2 minutes σ_{ti}= 1 minutes)

Performance metric	t_b and t_i Deterministic (Scenario – E)		t_i as Normal distribution		t_i as Exponential distribution		t_i as Poisson distribution		t_i as Gamma distribution	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Level of warning (%)	83.4	1.7	83.4	1.5	83.4	1.7	83.5	1.6	83.4	14.4
Notification time (in min)	121.9	18.0	131	11.8	131.6	13.8	132	13.1	132.9	15.0

4.3.4 Summary of findings from the model

The behaviour of households as an unofficial warning channel was represented by four parameters. Sensitivity analysis has been conducted to explore the effect of uncertainties in parameters. Table 4.14 summarises the results of simulation experiments.

Table 4.14 Summary of experiment results

Scenario	Impact on the overall warning level	Impact on the overall notification time
Including unofficial warning channel (Table 4.7 & Figure 4.10)	Sensitive	Less sensitive
Uncertainty in P_d (Table 4.8)	Sensitive	No impact
Uncertainty in average t_b (Table 4.9)	No impact	Sensitive
Variation of t_b (Tables 4.10 & 4.11)	No impact	Less sensitive
Uncertainty in t_i (Table 4.12)	No impact	Sensitive
Stochasticity of t_i (Table 4.13)	No impact	Sensitive

- Even at high percentage of defaulters, the unofficial channel was found to have impact on the overall warning level (% warned).
- Excluding unofficial channel will underestimate the warning capability.
- Every 10% increase in defaulter houses, will result in 2.6% decrease in warning level.
- On comparing various scenarios (Section 4.3.3.5), the scenario - E, {all four neighbours with uniform distribution, deterministic t_b and t_i} was found to be a moderate representation of unofficial warning behaviour of the household.
- Model results showed that uncertainty in the 'assimilation time - t_b' at the household level has an impact on the overall notification time and not on the warning level.
- The 'time to inform' parameter uncertainty is found to be pessimistically represented using 'gamma distribution' and three other distributions 'Poisson, exponential and normal' are found to be having the same impact.

Based on the evidence from the prototype ABM, this thesis argues that the role of unofficial channel, either voluntary or coordinated, will be a good means of augmenting warning capability.

4.4 **Configuration of ABM to ERGO city**

The previous section presented the ABM prototype model for warning dissemination in a hypothetical community of 1000 households. This ABM will be scaled up to have ERGO city evacuation details and further study the warning dissemination under various conditions. As the household level behaviour of warning dissemination has been implemented, tested and parameters of the model have been studied, the scale-up requires configuration of the modelled world to have the city details. The overall architecture of the models has been presented in the methodology chapter (Figure 3.3). The ERGO city evacuation zone details consist of a) households and its properties within the modelled area and b) evacuation route details. The evacuation route details are relevant for the transportation model and will be explained in Chapter 5.

Each household is provided a unique identification number. The properties of the household are id, location (x-coordinate, y-coordinate) and post-code. These household attributes are arranged as ordered comma-separated values in the input coordinate file 'ERGO-Household-Details.txt'. Each row in the input file represents one household detail. The end-user can load these household details in the setup stage into the modelling world. In run-time, the coordinate file is parsed and further one agent is created per household with properties as specified in the input file. The NetLogo model world has been re-sized to configure the ERGO city modelled. The zones that fall outside the evacuated zone are provided with id '999' and the evacuated zones are indicated with a two-digit postcode. The aggregate information about the household (e.g. family size), warning system details and unofficial channel behaviour are input into the model as explained in the next section.

4.5 **ABM for warning message dissemination - ERGO city case study**

This thesis adopts a case study approach in illustrating the ESFs and the integrated approach. The ERGO city case details have been presented in Section 4.3. EMAs responsible for ESF-1 will be keen to know the progression of warning dissemination from the onset of disaster (warning response curve) and the level of households warned within 90 minutes.

In total, there are 31617 households in the modelled area. Among the 19 zones to be evacuated, there are 9214 households. The number of evacuees to each household was assigned with an average of five per household. Only the resident households within the modelled area are considered in this thesis and are represented as households.

As a simplification, transient population and commuters are not included in the warning dissemination model. All the households are assumed to be occupied and the informant behaviour is represented using the parameters namely defaulter percentage, assimilation time and time to inform their neighbour. The ABM for city scale was developed using NetLogo software and Figure 4.11 is a screenshot of the ABM warning dissemination model.

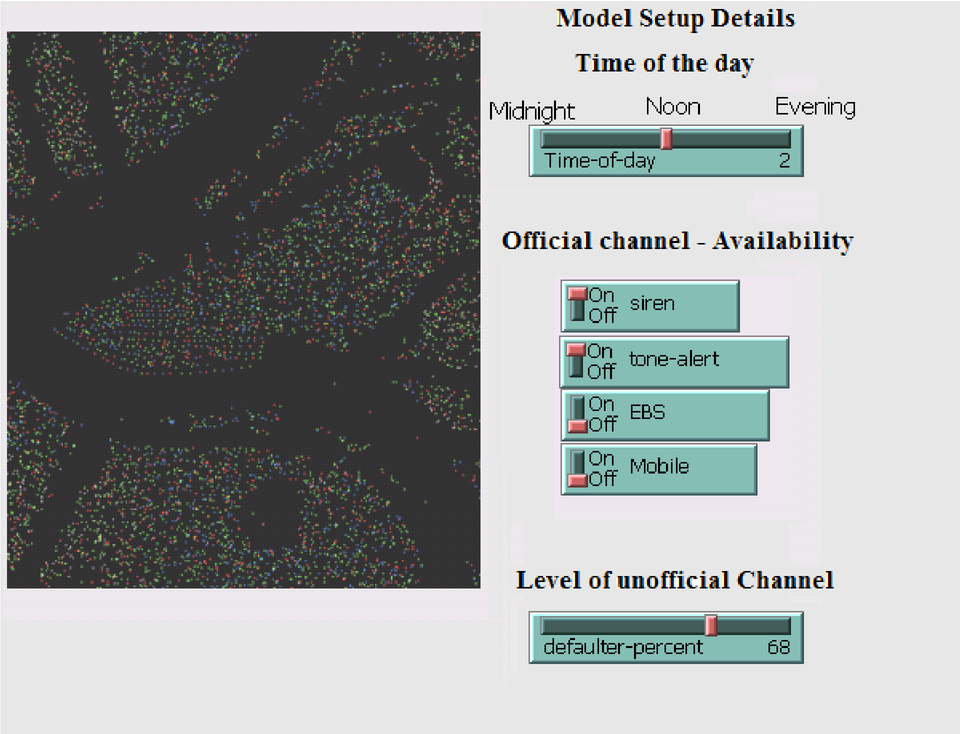


Figure 4.11 Screenshot of ABM for warning dissemination – City scale

Each agent in the model represents a single household unit. Multiple residential buildings (e.g. apartments) are not considered in this study as a simplification. From the onset of warning, the households states of warning and its behaviour prior to departure are described in Figure 4.1. Once the coordinate file is imported into the model canvas, the user can set the initial setup parameters namely time of the day, channel availability and level of unofficial channel. For each household, a parameter called ‘neighbourhood network level’ is provided at the set-up stage with a uniform discrete distribution of 4. During run-time, each household agent looks for neighbours in the eight pixels around it. For a non-defaulter household, the model would randomly select houses as many as ‘neighbourhood network level’ to be their neighbours. If there are only fewer houses available than the ‘neighbourhood network level’, the household would select all the available houses in 8 pixels as neighbours. The logic related to setting defaulter houses, initial seeds and informing their neighbours is similar to the description presented in the prototype model.

4.6 **Validity and reliability of simulation results**

ABM contains parameters that are represented using probabilistic distribution, for example percentage defaulters, uncertainty in the assimilation time and time to inform neighbours. During model execution, a set of households are selected to have household behaviour or attributes based on the probability distribution and random selection. For example, the initial seeds for warning dissemination are based on the first instance of receiving official warning message and houses are randomly chosen to be warned. In general, the outputs from the models might be influenced by the random selection in the model logic. Moreover, a single-run result has a potential to be biased by the random selection set. In order to understand the robustness of the solution and its reliability in providing a point estimate (one trial result) of the actual value of KPI, the model need to be executed for experimental trials and then the randomness in the results are to be observed.

Two set of experimental trials with 'official channel configuration' were conducted by repeatedly executing the model, keeping other input parameters constant. The analyses from prototype model indicated that 20-minutes stopping time was enough to observe any significant incremental warning in the modelled community. It was assumed that this finding was applicable to city scale. The official channel effectiveness was available only for 90 minutes. In many official channels, the incremental progression of cumulative coverage was small and diminishing beyond 60 minutes. Keeping this in mind, the stopping time was taken as 45 minutes, which includes an allowance of 25 minutes for variation due to scale-up from prototype to city. And the 'run-time' of the model was taken as 135 minutes (90 + 45) which is well above the ERGO city case of understanding warning dissemination within 90 minutes.

It was calculated that 10 runs are enough to capture the variation in the model output due to uncertainty in model parameters. In each trial, the model was executed 10 times. All the four channels were used in the first trial and only 'siren and public announcement' in the second as scenarios for peak and moderate levels of official channel availability. In both trials, the time of the day for warning dissemination is noon and the value of defaulter percentage is 68%. Table 4.15a and Table 4.15b respectively show the results of individual trials for the two experiments. Mean and standard deviation of KPI as well as intermediate monitoring variables were obtained as descriptive statistics of each experiment. Additionally, the standard error of mean (SE_{mean}) was computed for each KPI using the formula:

$$SEmean = \frac{s}{\sqrt{n}} \qquad \dots (4.1)$$

Where s – is the standard deviation of the sample mean
n – is the number of samples.

The smaller the value of standard error, lower will be the spread of means estimated from the model and more reliable a single trial value is. As the EMAs will be interested in the KPIs of the evacuated zone, the standard error results are presented in Table 4.15c.

- The results showed that the values of ‘warning level’ had a standard error 0.00093 and 0.00149 respectively for two set of trials, which is very low compared to the average values namely 80.24% and 61.95%. The coefficient of variation (standard deviation/mean) was found to be 0.59% and 0.48% and these indicate that the spread of individual trial values is within these values for the two set of trials.
- For the notification time, the standard errors were 1.03 and 2.06 respectively for two trials which are about 3.19% and 6.27% of the means 102.2 and 104.1 minutes.
- Third, for the number of households in the evacuated zone which received first warning from the neighbours as a measure of unofficial channel’s impact, the standard error was about 8.57 and 8.94 houses which are about 3.17% and 3.01% of the means 855.1 and 939.8 houses respectively.

The loss of information/inferences from model results to the EMAs (end-users of the model) at this level of standard error is argued to be small and less impactful in changing evacuation warning response due to the error. All the three KPI values showed low values in error between the experimental trials, and this infers the estimated mean is robust from the ABM and one trial run is reasonably accurate for the purpose of planning warning dissemination.

Table 4.15a Experimental trials of ABM to determine the accuracy between runs.

All four official channels and P_d = 68%	Experimental trial 1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
1. Model control variables												
Total houses in the data file	31617	31617	31617	31617	31617	31617	31617	31617	31617	31617		
Number of houses in evacuation zone	9214	9214	9214	9214	9214	9214	9214	9214	9214	9214		
Total resident population	159063	158229	158629	159092	158596	158337	158340	158350	159074	158922	158663.2	346.83
Total number of evacuees	46395	46058	46107	46122	46334	46166	46290	46234	46365	46544	46261.5	152.40
Family size (average)	5.03	5	5.02	5.03	5.02	5.01	5.01	5.01	5.03	5.03	5.02	0.01
Overall ERGO city												
Number of defaulter houses	15540	15506	15627	15538	15539	15612	15545	15675	15636	15552	15577.0	55.61
Number of houses warned	25428	25419	25559	25496	25595	25605	25396	25482	25559	25514	25505.3	74.41
Only evacuating household												
Number of defaulter houses	4427	4512	4555	4492	4540	4529	4503	4630	4566	4541	4529.5	52.96
Number of houses warned	7363	7354	7436	7381	7422	7456	7418	7313	7376	7411	7393.0	43.28
2. KPI - output metrics												
Only evacuating household												
Warning level	79.91%	79.81%	80.70%	80.11%	80.55%	80.92%	80.51%	79.37%	80.05%	80.43%	80.24%	0.00
Notification time	99	103	107	97	100	104	99	103	105	105	102.20	3.26
Houses receiving first warning from neighbours	901	857	880	833	825	841	869	813	873	859	855.10	27.13
Overall ERGO city												
Warning level	80.43%	80.40%	80.84%	80.64%	80.95%	80.98%	80.32%	80.60%	80.84%	80.70%	80.67%	0.00
Notification time	112	118	111	104	114	106	110	105	105	105	109.00	4.74
Houses receiving first warning from neighbours	3181	3209	3224	3195	3148	3179	3119	3100	3143	3097	3159.50	44.97

Table 4.15b Experimental trials of ABM to determine the accuracy between runs.

Siren + PA (official channels) and P_d = 68%	Experimental run 1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
1. Model control variables												
Total houses in the data file	31617	31617	31617	31617	31617	31617	31617	31617	31617	31617		
Number of houses in evacuation zone	9214	9214	9214	9214	9214	9214	9214	9214	9214	9214		
Total resident population	158506	158150	158182	158413	159139	158998	159336	158846	157902	158343	158581.5	473.99
Total number of evacuees	46138	46104	45953	46170	46325	46427	46154	46308	45865	46196	46164.00	168.39
Family size (average)	5.01	5	5	5.01	5.03	5.03	5.04	5.02	5	5.01	5.02	0.01
Overall ERGO city												
Number of defaulter houses	15611	15591	15547	15586	15624	15649	15675	15721	15665	15522	15619.10	60.65
Number of houses warned	19812	19812	19898	19887	19776	19683	19839	19770	19695	19781	19795.30	70.96
Only evacuating household												
Number of defaulter houses	4520	4580	4449	4563	4517	4516	4555	4577	4531	4481	4528.90	41.95
Number of houses warned	5675	5688	5758	5738	5736	5685	5695	5692	5710	5706	5708.30	27.15
2. KPI - output metrics												
Only Evacuating household												
Warning level	61.59%	61.73%	62.49%	62.27%	62.25%	61.70%	61.81%	61.78%	61.97%	61.93%	61.95%	0.00
Notification time	104	94	114	99	101	98	104	111	104	112	104.10	6.52
Houses receiving first warning from neighbours	933	897	990	937	984	926	917	932	935	947	939.80	28.30
Overall ERGO city												
Warning level	62.66%	62.66%	62.93%	62.90%	62.55%	62.25%	62.75%	62.53%	62.29%	62.56%	62.61%	0.00
Notification time	112	113	114	121	119	113	109	111	108	116	113.60	4.12
Houses receiving first warning from neighbours	3458	3372	3501	3506	3465	3339	3521	3351	3354	3442	3430.90	70.64

Table 4.15c Summary statistics of ABM experimental trials

Scenario	Mean	Standard deviation	Standard Error	Coefficient of variation
All four channels system at noon with P_d = 68%				
Warning level (%)	80.24	0.00	0.00	0.59
Notification time (minutes)	102.20	3.26	1.03	3.19
Houses warned by neighbours	855.10	27.13	8.58	3.17
Siren and PA at noon with P_d = 68%				
Warning level (%)	61.95	0.00	0.00	0.48
Notification time (minutes)	104.10	6.52	2.06	6.27
Houses warned by neighbours	939.80	28.30	8.95	3.01

As there were no real-life data of actual evacuation results for the ERGO city (being a hypothetical case study), the validity of these results with the actual field observations could not be ascertained and has scope for further research study. Prior to implementing in the actual evacuation planning, it is desirable to evaluate with empirical field observations of the modelled area which is often expensive to collect during evacuation. The process map of household's warning informant behaviour was formulated using literature and representative values were chosen from the existing evacuation studies. It could be argued that such an approach of ABM has a potential to provide robust estimates for warning dissemination performance, give greater confidence on single trial results and possibly support EMA's warning preparedness initiatives using an ABM.

4.7 **Scenario on uncertainty in warning dissemination - results and discussion**

The role of unofficial channel needs to be studied in conjunction with official channel, as the household receiving the message from the latter form the initial seeds. In order to understand the impact of unofficial warning channel, its uncertainties on overall warning dissemination, various scenario experiments were identified as discussed below. The effectiveness of these depends on the timing of the day (Stern and Sinuany-Stern 1989) and the availability of the channel (Parker and Handmer 1998, Sorensen 2000). This thesis will investigate these two aspects on official warning channel along with the role of unofficial channel and its uncertainties. These scenarios presented in the following sub-sections would address the research questions (Q2 and Q3) of the thesis pertaining to ESF-1.

4.7.1 Impact of time of the day on warning dissemination

Households within a city on a normal day are involved in different activities as summarised in the average time budget (Figure 4.12) reproduced from Roger and Sorensen (1991). This thesis focuses only on the residential household evacuation, and the warning dissemination to the commuters and transient population have been excluded from the model as a simplification. For understanding the impact of time of the day on warning dissemination, three scenarios were identified as representative for a day namely: midnight (0000 hours), noon (1200 hours) and evening (1900 hours). For each time, the proportion of people involved in various activities was measured from Figure 4.12 and tabulated in Table 4.16.

Figure 4.12 Average time budget – location/activity of households (Reproduced from Roger and Sorensen 1991, Figure 2, p125)

Table 4.16 Proportion of households in different activities for times of the day

Household Activity	Midnight	Noon	Evening
Home asleep	90	5	5
Indoors at home	5	40	50
Watching TV	3	7	25
Listening to Radio	0	4	3
Others excluded – Transit and Outdoors	2	44	17
Net Total = 100 - excluded	98	56	83

As presented in the literature review, there are five fundamental activities identified for indicating at the household level. This thesis assumes that the residential houses are occupied at the time of warning onset, and hence the activities such as in transit and outdoors have been excluded as a simplification. The unit of analysis is at the household level. If a member of family is at work or school, the possibility of them receiving a warning message is even though uncertain and has not been factored into the thesis as a simplification. As the thesis is focusing on the household level, the activity/location of the household is considered as equal for all the family members. It is assumed that when one member of the family receives the warning message, the household is considered to be warned.

Figure 4.13 'Average dissemination time' for alternative warning system technologies (Reproduced from Sorensen 2000, Figure 1, p122)

No two warning channels are alike in their effectiveness (both coverage and notification time), which is contingent upon whether a household has access/connected to the channel and the capability of the warning channel to alert many households. For example, a siren can alert a household even at midnight when they are asleep, although the time for the household to become awake and be warned is variable. From the graph, it can be observed that, for an average 10-minutes duration, the rate of sirens alerts (capability) is much higher than telephones.

There are four warning channels for which the effectiveness was obtained (Figure 4.13) from the onset of warning. The channels are sirens, tone alert (PA), media (EBS – emergency broadcast system) and Telephone (mobile). This thesis will use these four channels as official warning system. Based on the average warning channel profile (Figure 4.13), the cumulative per cent of houses warned for each warning channel was obtained for every five-minute interval. Depending on the nature of warning channel, their warning average effectiveness needs to be scaled down/adjusted for different times of the day. When the user selects on/off switch indicating the availability of channel in the ABM screen, these effectiveness values are internally set.

Table 4.17 presents a quantified estimate of adjustment (Roger and Sorensen 1991, Table 2, p 126) for each warning channel depending on the activity of household. Each of the capability value is represented as C_{ij},

where,

i – is the index for household activity {1, 2, 3 and 4}

j – is the index for official channel {1, 2, 3 and 4}

Table 4.17 Channel effectiveness for different activities (Roger and Sorensen 1991, Table 2, p126)

Even though these estimates were for Pittsburgh, United States, it is assumed to be applicable to the ERGO city. With the advancement of technology and sophistication in warning channel from the time of that study, these values may not be true representation to the present time. Conventional Sirens and PA systems have not changed. But some cities have modern remotely operated PA systems with voice-over capabilities (e.g. Telegrafia) which were unavailable until recently, and the effectiveness of these systems needs to be measured in further work. These are some of the limitations of this thesis work, but the methodology proposed in this thesis is still valid.

As the ‘time of the day’ will affect the activity of the household (Table 4.16), this would in turn affect their connectivity to the official channels. On the other hand, the impact of time will affect the outreach of warning channels as presented in Table 4.17. For each time of the day, the proportion of people at various activities L_j (Table 4.16) was multiplied with activity-based channel effectiveness (Table 4.17) C_{ij} to obtain the adjusted channel coverage.

Channel effectiveness for an activity j

$$AC_{ij} = L_j . C_{ij} \qquad \ldots (4.2)$$

Adjusted channel effectiveness

$$AC_j = \sum_{i=1}^{4} L_i . C_{ij} \qquad \ldots (4.3)$$

AC_{ij} indicates the maximum coverage that can be obtained from channel j for the chosen time of the day. As the warning effectiveness curve indicates the average value of cumulative coverage, this is adjusted/scaled down to obtain adjusted channel capacity as shown in Equation 4.3. And thus the impact of time of the day (activity of the household) has been obtained for each time step as presented in Figure 4.14

Time-activity budget, channel capability, activity adjustment and the warning dissemination curves for different times were assumed to be applicable to the ERGO City for illustration of the proposed method of integrated warning dissemination planning. This thesis empirically quantifies the household informant behaviour using parameters and further studies the warning dissemination at a city scale. This methodology could generate evidence base for the EMAs on the role of household behaviour as informants and its implications for warning dissemination.

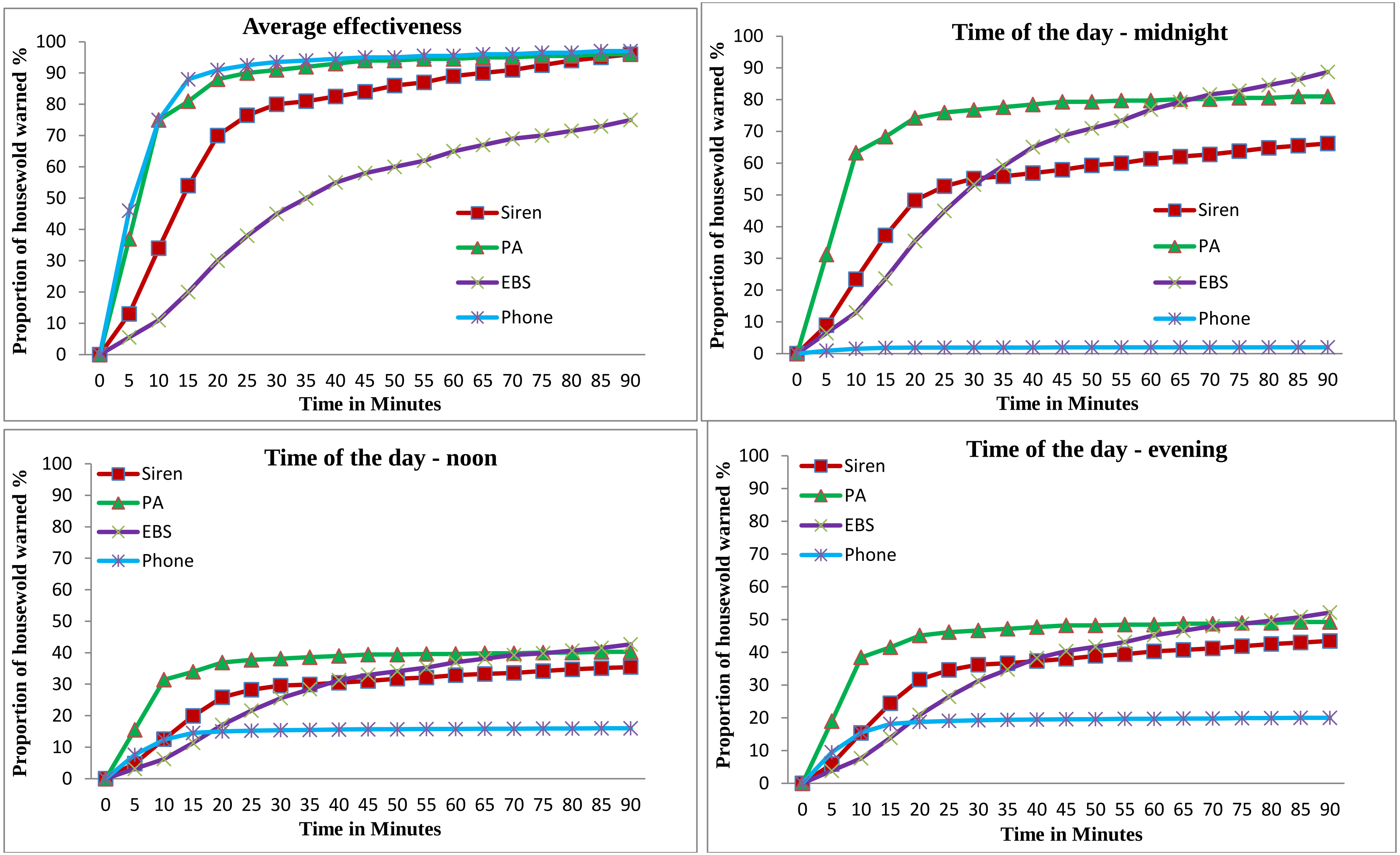


Figure 4.14 Warning channel coverage at average effectiveness (top left), midnight (top right), noon (bottom left) and evening

The ABM was executed with all the four official warning channels for different time of the day. Each official channel's effectiveness was adjusted from the peak value for the impact of time of the day, activity of household based on their location. This procedure was elaborated in the previous section and the estimated official warning channel values were internally selected with the model once the user selects 'time of the day' slider in the input screen. The value of defaulter percentage (P_d) was assumed to be 68% for all the cases. The results of model run for this scenario (time of the day) with and without unofficial channel has been presented in Figure 4.15 and Table 4.18a and Table 4.18b.

When all the four channels are working, it can be observed from the figure that the progression of 'cumulative pecent houses warned' is high in all the cases within 30 – 50 minutes from the onset of warning dissemination. There is very little increase beyond that time. Among the three cases, noon has the lowest level of warning given the higher proportion of households is not connected to media channels.

From Table 4.18a and Table 4.18b, the difference between the warning level at 'midnight' (optimistic case) and 'noon' (pessimistic case) is about 7.87% (93.51 - 85.64 %) while unofficial channels were considered. The notification time is the same for noon and midnight and varies only by 4 minutes. In comparing of 'time of the day' with and without unofficial channel, the difference in the level of warnings is 3.11%, 6.13% and 4.54% respectively.

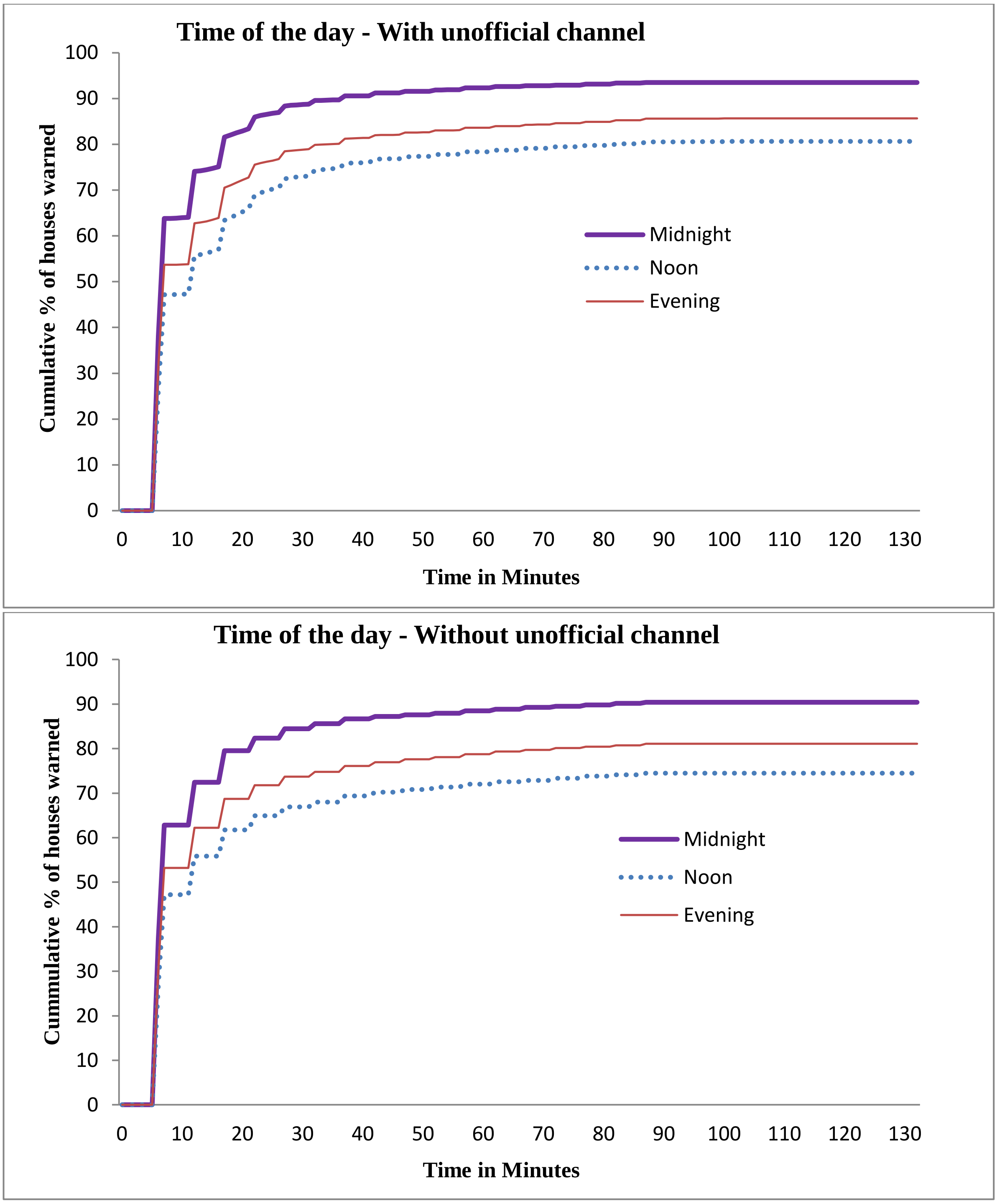


Figure 4.15 Warning response curves for the scenario 'time of the day' with and without unofficial channels

The higher the 'number of houses receiving the first warning from neighbours' (FW) more will be the number of informants (for a constant P_d) and hence this parameter can serve as a KPI for measuring relative effectiveness of different scenarios. The average FW was found to be 712 houses. Number of houses receiving the first warning from neighbours is highest in the noon scenario (848) which is 35% [(848-551)/848] and 12.8% [(848-739)/848] more than for the scenario midnight and evening, respectively.

Even though the level of warning was the lowest for the noon scenario, the impact of unofficial channel is relatively higher during noon compared to midnight/evening. This also triangulates with the higher number of houses receiving first warning from neighbours during noon. For the purpose of planning, noon could be considered as a worst case on the time of the day variable. As all the four channels are functioning in these cases, the level of warning without unofficial channel is high enough to reach the household within the overall warning capability. Thus, when all the four channels are working, the unofficial channel at most could increase by 6.13%. This thesis will further investigate the level of unofficial channel impact at the worst case condition, i.e. only one official channel namely siren during noon time of the day. The results for this experiment are presented in Table 4.18b.

In contrast to the earlier scenario of all four warning channels with unofficial channel, the difference between the warning level at ‘midnight’ (optimistic case) and ‘noon’ (pessimistic case) was about 13.89% (57.81 – 43.92 %). The difference (13.89%) is much higher compared to the result when all four channels were working, i.e. 7.87%. In comparing the ‘time of the day’ with and without unofficial channel, the difference in the level of warnings is 9.26%, 7.72% and 9.13% respectively.

The notification time results varied over the range 114-119 minutes for all the three times of the day. Number of houses receiving the first warning from neighbours is highest in the ‘midnight’ scenario (1082), which is 20% ((1082 - 860)/1082) and 18.1% ((1082-886)/1082) more than the results of scenarios in ‘noon’ and ‘evening’, respectively. The average FW was found to be 942 houses. Number of houses receiving their first warning is almost double for midnight scenario between all four channels and worst case (i.e. only siren). When the ‘official channel coverage’ is below sub-optimal levels (say due to failures/unavailability), ‘the role of unofficial channel in midnight’ could be argued as prominent.

Table 4.18 a - Warning dissemination KPI comparison for the scenario 'time of the day' with all four channels

Sl.No.	Time of the day	With unofficial channel Midnight	With unofficial channel Noon	With unofficial channel Evening	Without unofficial channel Midnight	Without unofficial channel Noon	Without unofficial channel Evening
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses within evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	158511	157800	159093	158971	158184	158937
	Total number of evacuees	46271	45675	46204	46165	46158	46224
	Family size (average)	5.01	5	5.03	5.03	5.003	5.03
	Overall ERGO city						
	Number of defaulter houses	15627	15620	15611	31617	31617	31617
	Number of houses warned	29485	25493	27156	28572	23401	25577
	Only evacuating household						
	Number of defaulter houses	4554	4535	4582	9214	9214	9214
	Number of houses warned	8616	7428	7891	8329	6863	7473
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	93.51%	80.62%	85.64%	90.40%	74.48%	81.10%
	Notification time	97	101	101	87	87	87
	Houses receiving first warning from neighbours	551	848	739	0	0	0
	Overall ERGO city						
	Warning level	93.26%	80.63%	85.89%	90.37%	74.01%	80.90%
	Notification time	107	115	106	87	87	87
	Houses receiving first warning from neighbours	2034	3152	2681	0	0	0

Table 4.18b Warning dissemination KPI comparison for the scenario 'time of the day' when only siren is working

Sl.No.	Time of the day	With unofficial channel Midnight	With unofficial channel Noon	With unofficial channel Evening	Without unofficial channel Midnight	Without unofficial channel Noon	Without unofficial channel Evening
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	159035	158882	158753	158109	158409	158457
	Total number of evacuees	46386	46196	46174	46109	46015	46070
	Family size (average)	5.03	5.03	5.02	5	5.01	5.01
	Overall ERGO city						
	Number of defaulter houses	15580	15546	15608	31617	31617	31617
	Number of houses warned	18451	12193	14005	15344	9456	11160
	Only evacuating household						
	Number of defaulter houses	4507	4571	4484	9214	9214	9214
	Number of houses warned	5327	3486	4047	4474	2775	3206
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	57.81%	37.83%	43.92%	48.56%	30.12%	34.79%
	Notification time	114	117	119	87	87	87
	Houses receiving first warning from neighbours	1082	860	886	0	0	0
	Overall ERGO city						
	Warning level	58.36%	38.56%	44.30%	48.53%	29.91%	35.30%
	Notification time	124	119	119	87	87	87
	Houses receiving first warning from neighbours	3758	3066	3214	0	0	0

In summary, the role of unofficial channel is more prominent when the official channel is in 'worst case' measured in terms of (a) warning level and (b) number of houses receiving first message from neighbours. As more houses will receive their message from neighbours, it takes a longer notification time in comparison between all four channels and worst case. The level of unofficial channel's impact is highest for 'midnight' scenario in contrast to 'noon' when all channels are functional. In contrast to the findings from the prototype model, the difference in the level of warning between no unofficial channel (Scenario A) and uncertain assimilation time with unofficial channels (Scenario I) was 31.8% = 83.2% - 51.4% (Table 4.7). The level of impact was much lower in the city scale and yet significant to support the role of unofficial channel during official channel failures. It must be observed that these results of warning dissemination are also dependent on the availability of warning channels and the percent defaulters (assuming a representative value P_d = 68%). This thesis will further investigate these two aspects in the following two sections.

4.7.2 Official channel vulnerability and failure scenarios

An article about the deadliest catastrophe tsunami 2004 with fatality over 200,000 describes the failure of EWS as "despite the presumed ubiquity and power of advanced technologies including satellites and the internet, no advance warning was given to the affected coastal populations by their governments or others" (Samarajiva 2004). This disaster has become a wake-up call for reviewing the EWS practises (including institutional structures) and making it a more 'people-centred' warning system (UNISDR, 2006a). There is also need to understand the propensity of failures of official channels and the reasons behind it.

Official channels are often reported to be vulnerable and fail during disasters (Parker and Handmer 1998, Sorensen, 2000). "*Communication problems, due to equipment and human failure, are the most significant causes of poor warning dissemination*" (Sorensen, 2000, p122). A study after Hurricane Katrina (Banipal 2006) found that "*breakdown of backhaul circuits, flooding of telephone exchanges and disruption of electricity contributed to failure of communication systems*". The impact on the warning system itself due to the hazard raises the need for designing a suitable combination of channels for the planned threat scenarios instead of taking an all-hazards approach. This entails an understanding of the vulnerability of each warning channel. Technology-sophisticated channels (like emergency broadcast systems; auto-dialler systems) are dependent on other critical resources like electricity and telecommunication network function. These resources too are vulnerable in a large-scale emergency.

For EMAs preparing for warning dissemination, a checklist prepared by the Early Warning Consortium (UNISDR 2006a) is a key and practical document for ensuring preparedness. One of the items about '*Effective communication systems (refers to warning channel) and Equipment installed*' in the checklist (Key Element 3, p7) states that "*Equipment maintenance and upgrade programme implemented and redundancies enforced so back-up systems are in place in the event of a failure.*"

It is essential to understand the vulnerability of warning system level (including the clearly identified roles of transferring forecasting messages from scientists for dissemination to the public) and also at the individual channel level. The warning system's institutional structure, although key, is considered beyond the scope of this thesis. Each channel depends on other resources (e.g. electricity) and even act as couplet to 'notify' the public with details. For example, a siren cannot be a standalone channel.

- By merely raising loud tone, unless the public are trained to interpret, they may not understand the meaning of it.
- A secondary channel (e.g. radio) is essential to provide details of the evacuation (location, intensity and timing) of the imminent/ongoing disaster.

Hence, the EMAs must understand the vulnerability of individual channels and also understand the essential supporting role with other channels. The dependency and limitation of each official channel has been presented in the literature review (
Table 2.6). Some of the warning channels require installation of sophisticated machinery, software and personnel to operate such as UMS, Gedicom/Domino, etc. When telecom network-based mass broadcast system (e.g. UMS) is fully functional, it claims to alert all the households in a very short duration, and no time-series values of its effectiveness is currently available. Any failure in the equipment or technology system or not planning for backup systems could cause 'technology failure'. These systems are dependent on telephone networks including routers, exchange units and satellites that add to the complexity of reasons why an official channel could possibly fail.

In Japan, a 2011triple-disaster event (i.e. earthquake-tsunami-nuclear power plant failure) has lead to shutdown of power plants and subsequent evacuation. Even though this was a controlled shut down, it does highlight the potential for critical infrastructure to fail during emergencies. During cyclone Yasi (2011) in Australia, about 61,000 households had no electricity (Taylor 2011a). During non-availability of official channels, the households to be evacuated without 'evacuation information' (location, intensity, etc.) could lead to confusion among the public even impeding their decision to evacuate. Un-warned household are subject to possible fatality. EMAs often prepare the public to have battery-operated radios in the emergency kit in campaigns like Go-in Stay-in and Tune-in. This serves as a precaution to be informed even during power outage. Some of the official channels that require electricity for operation could possibly fail due to 'electricity failure'.

On one hand, the household may not be able to access the channel (e.g. TV) and on the other hand a large-scale power-cut could disrupt even the technology-sophisticated channels. What could be the level of warning dissemination due to unofficial channels during these failures? These two failures and its implication on overall warning dissemination need to be investigated.

Table 4.19 presents the failure scenarios of the four channels, and the dissemination of warning could be studied using ABM.

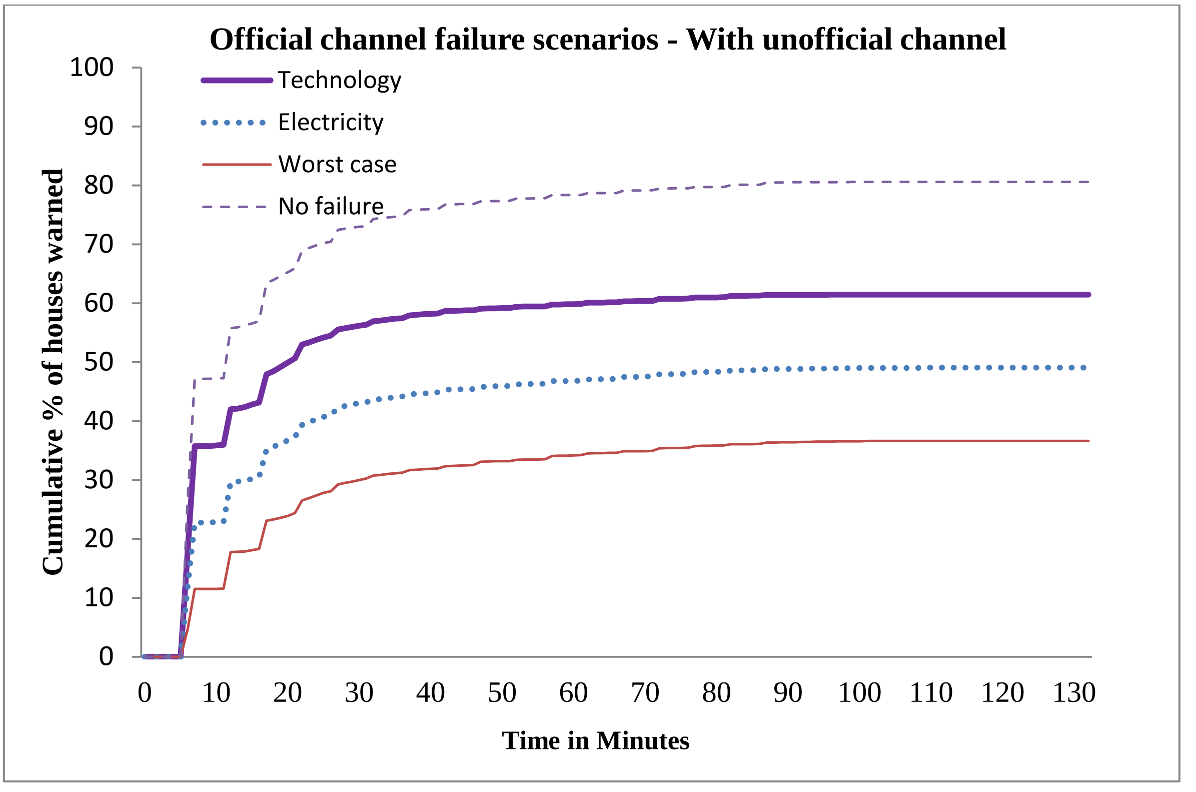
Table 4.19 Official channels available during various failure scenarios

Failure Scenarios	Siren	PA	EBS	Mobile
Optimistic case	On	On	On	On
Technology failure	On	On	Off	Off
Electricity failure	On	Off	Off	On
Worst case	On	Off	Off	Off

The ABM was sequentially executed with these scenarios, keeping the time of day as noon and the other parameters constant, namely defaulter per cent (Pd = 68%), assimilation time and 'time to inform a neighbour'. For each of these four scenarios, the model was executed with and without unofficial channel and the results are presented in Table 4.20 and Figure 4.16.

Table 4.20 Impact of unofficial channel on 'warning dissemination performance' during 'failures in official channel'

		With unofficial channel				Without unofficial channel			
Sl.No.	Official channel Failure	No	Technology	Electricity	Worst	No	Technology	Electricity	Worst
1.	**Model control variables**								
	Total houses in the data file	31617	31617	31617	31617	31617	31617	31617	31617
	Total number of houses (within evacuation zone)	9214	9214	9214	9214	9214	9214	9214	9214
	Total resident population	157800	158504	158209	158529	158184	158474	158630	159070
	Total number of evacuees	45675	46430	46164	46192	46158	46406	45987	46401
	Family size (average)	5	5.01	5	5.01	5.003	5.01	5.02	5.03
	Overall ERGO city								
	Number of defaulter houses	15620	15625	15543	15614	31617	31617	31617	31617
	Number of houses warned	25493	19604	15669	12066	23401	16889	12684	9426
	Only evacuating household								
	Number of defaulter houses	4535	4548	4465	4571	9214	9214	9214	9214
	Number of houses warned	7428	5661	4521	3375	6863	4975	3701	2792
2.	**KPI - Output metrics**								
	Only evacuating household								
	Warning level	80.62%	61.44%	49.07%	36.63%	74.48%	53.99%	40.17%	30.30%
	Notification time	101	96	127	112	87	87	87	87
	Houses receiving first warning from neighbours	848	922	916	743	0	0	0	0
	Overall ERGO city								
	Warning level	80.63%	62.00%	49.56%	38.16%	74.01%	53.42%	40.12%	29.81%
	Notification time	115	113	119	112	87	87	87	87
	Houses receiving first warning from neighbours	3152	3327	3358	2885	0	0	0	0



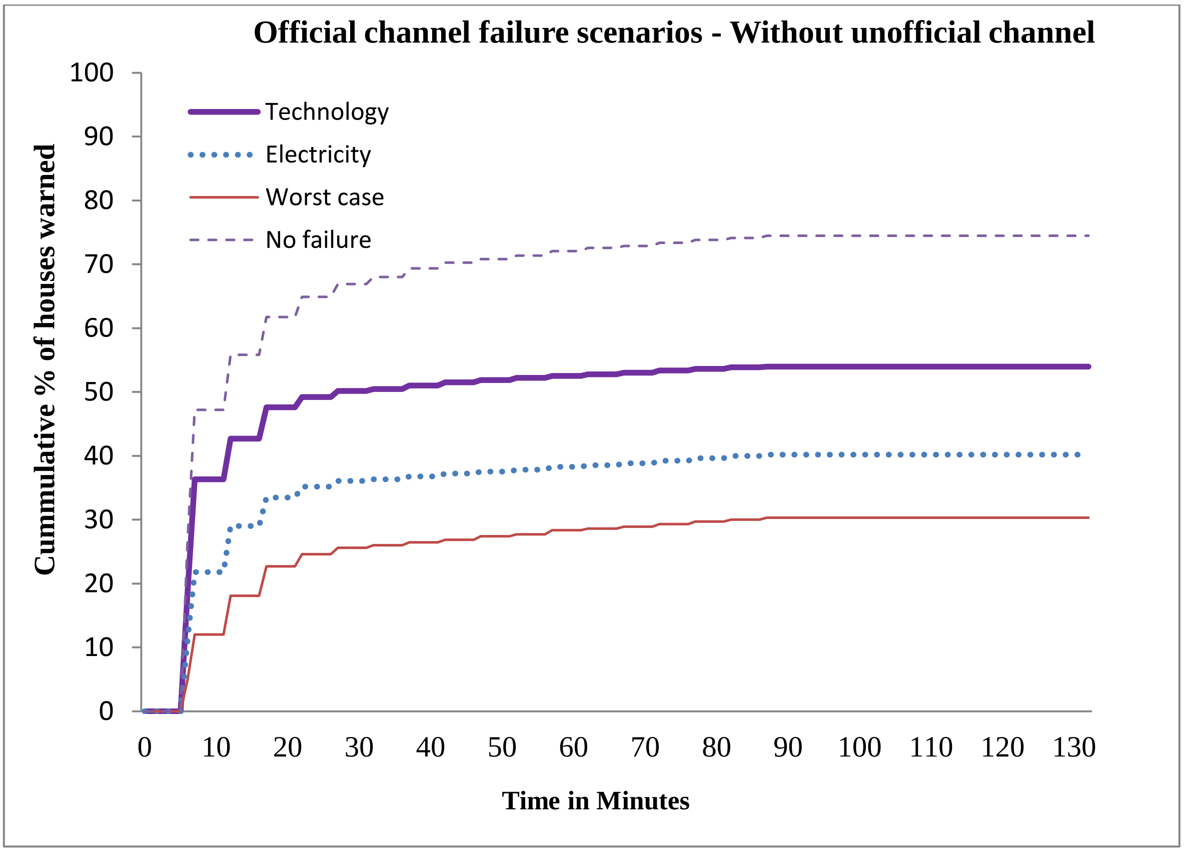


Figure 4.16 Warning response curves for various failure scenarios at noon

From Figure 4.16, it can be observed that the progression and the level of impact are similar for pair-wise comparison of including or excluding unofficial channels. From Table 4.20, the results from the model show that for cases with unofficial channel, the difference in the warning level between the optimistic scenario (no failure) and pessimistic scenario (only siren) was about 43.99% (80.62-36.63%). This highlights the wide range over which the failures overall warning level could be impacted due to failures. The ‘level of warning’ during technology failure and electricity failure scenarios was 61.44% and 49.07%, respectively.

On the other hand, for scenarios without unofficial channel, the difference in the warning level between the optimistic scenario (no failure) and pessimistic/worst scenario (only siren) was about 44.18% (74.48 - 30.3%). The ‘level of warning’ during technology failure and electricity failure scenarios was 53.99% and 40.17%, respectively.

On pair-wise comparison of including/excluding the unofficial channel, ‘level of warning’ results were lower for all the scenarios. The difference in warning level due to impact of unofficial channel was 6.13%, 7.45%, 8.9% and 6.33% respectively for the four failures with average of 7.2%. Even though the ‘difference between optimistic and pessimistic cases’ for including and excluding unofficial channel was almost the same (about 44%), the level of impact due to unofficial channel is about 7.2% increase in the coverage.

The variation in the notification time for cases with unofficial channel was between 96 and 127 minutes. On the other hand, the notification time was constant at 87 minutes when unofficial channel was excluded. By including unofficial channel, some of the houses receiving at later stages (e.g. after 60 minutes) from the warning onset will be available to inform their neighbours after 70-80 minutes. From the warning response curve (Figure 4.16), these houses though fewer in number cause the delay in the notification time value.

Table 4.20 summarised that for cases with unofficial channel, the difference in number of houses receiving first warning (KPI-3), between the highest value for the 'technology failure' case and the lowest during 'no failure' was 105 houses (922 – 743). Number of houses receiving the first warning from neighbours is almost equal in ‘Technology failure’ (922) and Electricity failure (916). Compared to pessimistic (743) and optimistic official channel levels (848), the role of unofficial channel is more prominent in either of the failures based on warning levels and count of neighbour warned houses.

In summary, the results from ABM showed that the failures in official channel availability will have significant impact on the overall warning level to the order of 44%. By including the unofficial channel, the warning level will increase on an average by 7.2%. The notification time was longer in general by including the unofficial channel. As the level of unofficial channel (represented using P_d) might have an impact on the extent to which the warning dissemination happens, this thesis further investigates this by using the sensitivity of defaulter percentage variable.

4.7.3 Impact of the unofficial channel on overall dissemination – sensitivity of defaulter percentage

Not all houses will inform their neighbours. Two sets of analyses were studied using the ABM at defaulter level of 68%. When a higher proportion of people act as warning informants, more houses that might remain 'un-warned' may be receiving their first/only warning from neighbours. This cascading effect was investigated using the sensitivity analyses of the defaulter percentage variable. The ABM was executed sequentially by varying Pd = {0%, 20%, 40%, 60%, 80%, 100%} representing six discrete values within continuum between ideal case (all houses are informants) and no unofficial channel (none of the houses are informants). The level of informal channel depends on the cohesion level of the community.

Official channel combinations were so chosen to vary the 'overall official channel coverage' (OCoff) to vary between 30% and 80% when no unofficial channel was included. The combination of warning channel and the respective effectiveness was presented in Table 4.21 leading to scenarios CA-CF. All the other parameters were kept constant in all these cases namely assimilation time and time to inform neighbour. The ABM was executed for each of the six scenarios (CA-CF) for different Pd values between 0% and 100% and the results are tabulated in Table 4.22a to Table 4.22f, respectively.

Table 4.21 Scenarios of official warning system and its effectiveness without unofficial channel

Scenario	Official warning system	Time of the day	Overall effectiveness
CA	Siren	Noon	29.74%
CB	Siren + Mobile	Noon	40.72%
CC	Siren + PA	Noon	52.63%
CD	Siren + PA + Mobile	Noon	60.20%
CE	Siren + PA + EBS + Mobile	Noon	74.16%
CF	Siren + PA + EBS + Mobile	Evening	80.51%

For the pessimistic official channel Scenario CA, the results from the ABM showed that (Table 4.22a) the impact of defaulter sensitivity measured as the difference in the level of warning between the ideal households (P_d = 0%) and no unofficial channel (P_d = 100%) was 12.35% (47.15 – 34.79%). The maximum number of houses receiving a warning from neighbour (FWmax) will occur in an ideal community with all household as informants (P_d = 0%). FWmax was 1716 houses and FW decreased on an average by 267 houses when defaulter percentage increased by 20%. In comparison with the earlier results by keeping P_d = 68%, the impact on warning level is higher at 12.35% compared to the average of 7.2% respectively. The results of scenarios CB to CF are presented in Table 4.22b to Table 4.22f.

Table 4.22a Scenario – CA Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	158111	158590	159363	158568	158813	158457
	Total number of evacuees	46118	46250	46222	46057	46564	46070
	Family size (average)	5	5.02	5.04	5.01	5.02	5.01
	Overall ERGO city						
	Number of defaulter houses	0	5742	10427	14283	17443	31617
	Number of houses warned	15299	14160	13227	12445	11790	11160
	Only evacuating household						
	Number of defaulter houses	0	1712	3010	4211	5122	9214
	Number of houses warned	4344	4039	3673	3627	3460	3206
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	47.15%	43.84%	39.86%	39.36%	37.55%	34.79%
	Notification time	128	132	103	124	121	87
	Houses receiving first warning from neighbours	1716	1399	1087	914	736	0
	Overall ERGO city						
	Warning level	48.39%	44.79%	41.84%	39.36%	37.29%	35.30%
	Notification time	128	132	131	124	121	87
	Houses receiving first warning from neighbours	6354	5115	4166	3309	2640	0

Table 4.22b Scenario – CB Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	158361	158993	158913	158810	158583	158617
	Total number of evacuees	45968	46355	46718	46195	46526	46184
	Family size (average)	5.01	5.03	5.03	5.02	5.02	5.02
	Overall ERGO city						
	Number of defaulter houses	0	5706	10394	14194	17472	31617
	Number of houses warned	18851	17675	16741	16053	15417	12790
	Only evacuating household						
	Number of defaulter houses	0	1691	3015	4141	5150	9214
	Number of houses warned	5423	4979	4820	4611	4398	3758
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	58.86%	54.04%	52.31%	50.04%	47.73%	40.79%
	Notification time	111	109	120	111	97	87
	Houses receiving first warning from neighbours	1866	1501	1222	1008	786	0
	Overall ERGO city						
	Warning level	59.62%	55.90%	52.95%	50.77%	48.76%	40.45%
	Notification time	127	124	120	130	112	87
	Houses receiving first warning from neighbours	6792	5584	4464	3698	2968	0

Table 4.22c Scenario – CC Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	157737	158489	158780	158691	158092	158480
	Total number of evacuees	45877	46221	46023	46523	46259	46088
	Family size (average)	4.99	5.01	5.02	5.02	5	5.01
	Overall ERGO city						
	Number of defaulter houses	0	5751	10423	14279	17384	31617
	Number of houses warned	22475	21624	20712	20098	19375	16775
	Only evacuating household						
	Number of defaulter houses	0	1663	3042	4080	5051	9214
	Number of houses warned	6472	6220	6020	5784	5628	4828
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	70.24%	67.51%	65.34%	62.77%	61.08%	52.40%
	Notification time	128	108	105	105	109	87
	Houses receiving first warning from neighbours	1781	1463	1256	1037	821	0
	Overall ERGO city						
	Warning level	71.09%	68.39%	65.51%	63.57%	61.28%	53.06%
	Notification time	128	120	111	105	109	87
	Houses receiving first warning from neighbours	6546	5413	4540	3810	2996	0

Table 4.22d Scenario – CD Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	158126	158273	158366	158275	158585	158862
	Total number of evacuees	46322	46051	46317	46061	46290	46107
	Family size (average)	5	5	5.01	5	5.01	5.02
	Overall ERGO city						
	Number of defaulter houses	0	5767	10407	14260	17409	31617
	Number of houses warned	24182	23294	22622	21990	21502	19076
	Only evacuating household						
	Number of defaulter houses	0	1671	3038	4126	5066	9214
	Number of houses warned	6981	6744	6517	6420	6189	5546
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	75.77%	73.19%	70.73%	69.68%	67.17%	60.19%
	Notification time	113	89	98	112	102	87
	Houses receiving first warning from neighbours	1675	1372	1133	970	814	0
	Overall ERGO city						
	Warning level	76.48%	73.68%	71.55%	69.55%	68.01%	60.33%
	Notification time	121	122	121	112	109	87
	Houses receiving first warning from neighbours	6121	5113	4228	3486	2958	0

Table 4.22e Scenario – CE Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	158632	158295	158315	158241	158117	158108
	Total number of evacuees	46399	46134	46483	46048	45964	46196
	Family size (average)	5.02	5	5	5	5	5
	Overall ERGO city						
	Number of defaulter houses	0	5706	10415	14226	17397	31617
	Number of houses warned	27255	26564	26166	25676	25281	23383
	Only evacuating household						
	Number of defaulter houses	0	1677	3016	4062	5018	9214
	Number of houses warned	7880	7705	7584	7514	7274	6856
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	85.52%	83.62%	82.31%	81.55%	78.95%	74.41%
	Notification time	108	102	114	112	102	87
	Houses receiving first warning from neighbours	1565	1349	1119	947	794	0
	Overall ERGO city						
	Warning level	86.20%	84.02%	82.76%	81.21%	79.96%	73.96%
	Notification time	108	104	114	115	106	87
	Houses receiving first warning from neighbours	5717	4812	4048	3399	2814	0

Table 4.22f Scenario – CF Impact of the 'level of informant behaviour' (P_d) on the overall warning dissemination

Sl.No.	Sensitivity of informant behaviour	Pd = 0%	Pd = 20%	Pd = 40%	Pd = 60%	Pd = 80%	Pd = 100%
1.	**Model control variables**						
	Total houses in the data file	31617	31617	31617	31617	31617	31617
	Total number of houses in the evacuation zone	9214	9214	9214	9214	9214	9214
	Total resident population	159364	158157	158354	158228	158462	158322
	Total number of evacuees	46642	45882	46141	46303	46293	46267
	Family size (average)	5.04	5	5.01	5	5.01	5.01
	Overall ERGO city						
	Number of defaulter houses	0	5759	10362	14218	17360	31617
	Number of houses warned	28470	28165	27663	27433	27080	25484
	Only Evacuating household						
	Number of defaulter houses	0	1653	3019	4070	5078	9214
	Number of houses warned	8246	8203	7983	7975	7832	7398
2.	**KPI - Output metrics**						
	Only evacuating household						
	Warning level	89.49%	89.03%	86.64%	86.55%	85.00%	80.29%
	Notification time	99	102	100	100	98	87
	Houses receiving first warning from neighbours	1366	1144	977	814	696	0
	Overall ERGO city						
	Warning level	90.05%	89.08%	87.49%	86.77%	85.65%	80.60%
	Notification time	110	117	103	107	106	87
	Houses receiving first warning from neighbours	4897	4242	3631	2996	2527	0

The following are parameters that summarise the results for each scenario, and the summary statistics of these scenarios are presented in Table 4.23.

- OC_{off} – Coverage due to official channels only (P_d = 100%).
- WL_{max} – The maximum value of warning level (coverage) within one official channel scenario occurs at (P_d = 0%)
- WL_{i-n} – The difference in warning level between ideal community (P_d = 0%) and no unofficial channel within one official channel scenario.
- NT_{i-n} – The difference in notification time between ideal community (P_d = 0%) and no unofficial channel within one official channel scenario.
- FW_{max} – The maximum value for 'number of houses receiving first warning (FW) from neighbours' within one official channel scenario
- rFW – rate of increase in FW for every 20% increase in P_d

Table 4.23 Summary of ABM results for each scenario under various official coverage

Scenario	OC_{off}	WL_{max}	WL_{i-n}	NT_{i-n}	FW_{max}	rFW
CA	34.79%	47.14%	12.35%	41	1716	267
CB	40.79%	58.86%	18.07%	24	1866	286
CC	52.40%	70.24%	17.84%	41	1781	248
CD	60.19%	75.76%	15.57%	26	1675	235
CE	74.41%	85.52%	11.11%	21	1565	206
CF	80.29%	89.49%	9.20%	12	1366	184

This set of scenarios synthesises the role of unofficial channel impact by studying the impact of level of household informant behaviour (P_d) under various levels of official channel coverage. Figure 4.17 presents a 3D frontier curve that synthesises overall warning coverage (WL) with the level of official warning coverage (OC_{off}) and the level of unofficial warning (P_d). Figure 4.18 and Figure 4.19 present respectively the frontier curve for 'difference in warning level' WL_{i-n} and the 'number of houses warned by their neighbours' (FW).

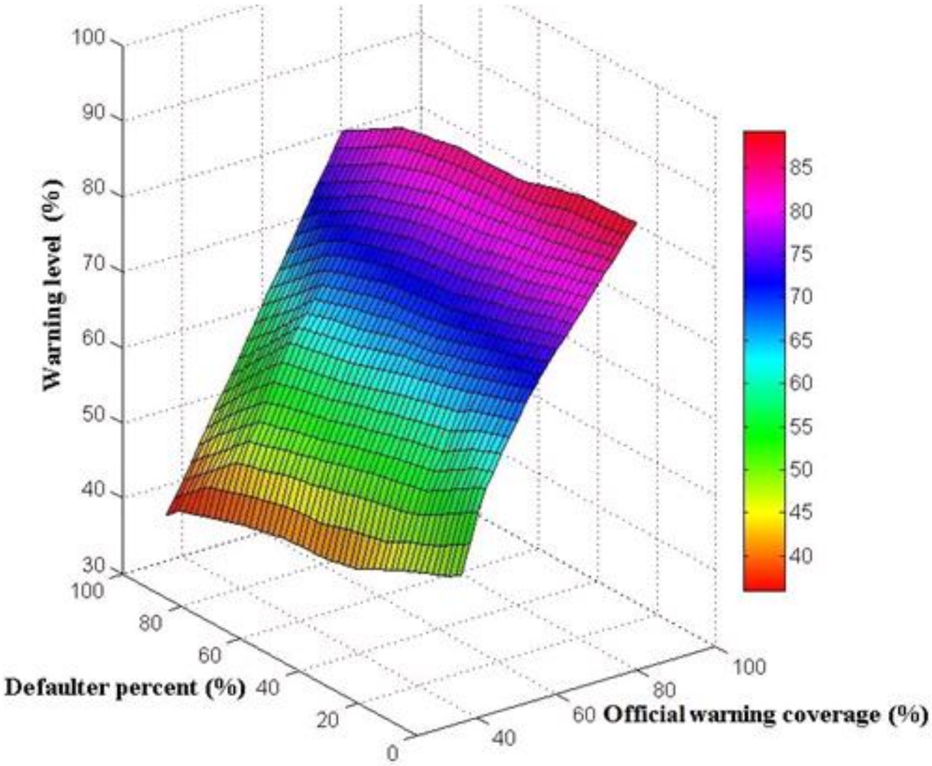


Figure 4.17 Frontier curve showing impact of unofficial channel (P_d) measured using warning levels

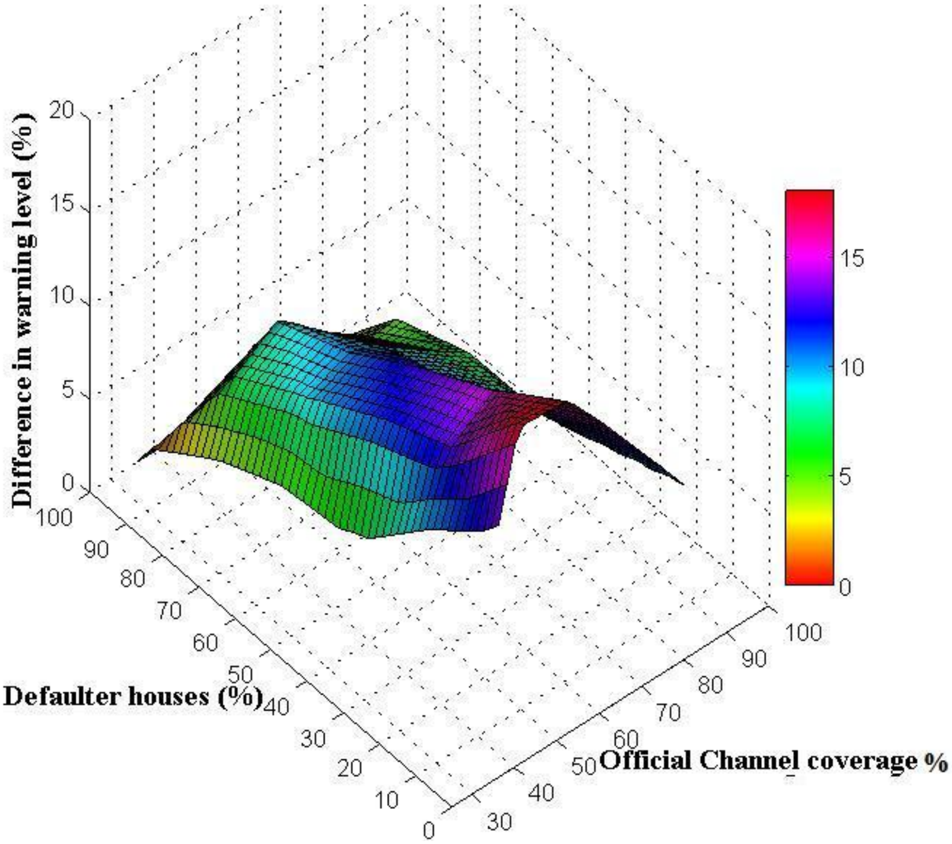


Figure 4.18 Frontier curve showing impact of unofficial channel (P_d) measured using difference in warning levels WL_{i-n}

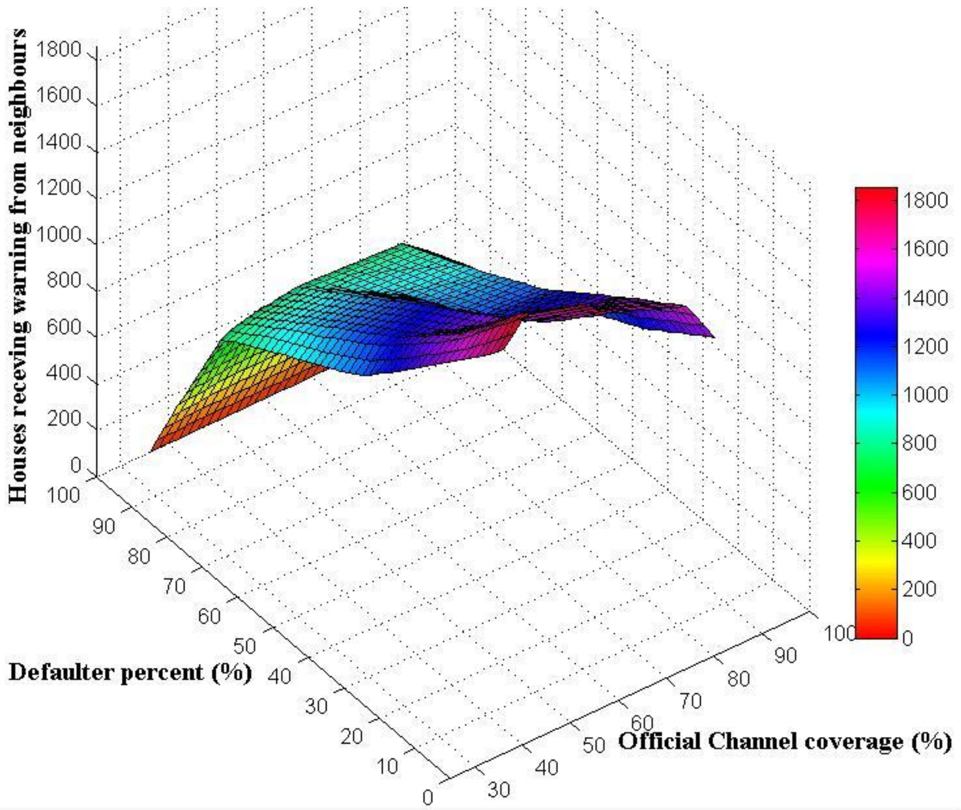


Figure 4.19 Frontier curve showing impact of unofficial channel (P_d) measured using houses warned by neighbours FW

It can be observed from Figure 4.18 and Table 4.23 that the maximum impact of unofficial channel occurs (measured using WL_{i-n}) when the official channel coverage is in the range 40-50% and with an increase in warning level by about 18%. When the official channel coverage reduces below 40%, a low number of people will become initial seed and cascade the information to others and hence the role of unofficial channel reduces further. On the other hand when the official channel coverage is beyond 50%, the role of unofficial channel reduces further. This may be due to a reason that a household has higher likelihood of receiving the first message from any of the official channel than from neighbours. This frontier takes a concave shape with a peak in the range 40-50%.

In comparison to the difference in warning level, the metric FW also shows similar trend as depicted in Figure 4.19. The maximum value of FW (around 1800) occurs in the optimal range of official channel availability (40-50%). The rate of decrease in FW (rFW) indicates a non-linear trend. EMAs will be able to better understand the dynamics between overall warning coverage, official channel and unofficial channel from the synthesised results.

Keeping the P_d factor aside, the impact of unofficial channels (with no prior information) will be in the range of 9-18% based on the level of channel availability.

4.8 **Discussion of findings from ABM for warning preparedness of a city**

How will an EMA responsible for warning dissemination be able to gain more confidence through preparedness? For the ERGO city evacuation, will they be able to warn in 90 minutes? EMAs are confronted to support their warning preparedness with evidence base in order to gain greater confidence in their capabilities. The following are some of the key findings on the warning dissemination theory based on simulation of ABM:

- Based on warning coverage as KPI, 'noon' was found to have the lowest level of warning dissemination (at P_d = 68%), when the official channel is at optimistic level (all the four channels are functioning) and pessimistic level (only siren is working)
- Based on the 'number of neighbour warned houses' (FW) as KPI, the impact of unofficial warning channel was more prominent in 'noon' and 'midnight' in the optimal and pessimistic official channel level, respectively.
- When the official channel is at optimistic level, the impact of unofficial channel (at P_d = 68%) was found to increase the warning coverage by 6.13% in 'noon'. The overall average impact in a day was found to be 4.59%.
- When the official channel is at pessimistic level, the impact of unofficial channel (at P_d = 68%) was found to increase the warning coverage by similar proportion in 'midnight' (9.26%) and 'evening' (9.13%). The overall average impact in a day was found to be 8.7%.
- For residential households, noon is relatively vulnerable for warning dissemination.
- For a low level (at P_d = 68%) of public acting as informants, the average impact of unofficial channel on warning level ranges between 4.6% and 8.7%.
- Depending on the vulnerability of official channels, the level of warning dissemination impact could vary between 30% and 80%, and hence understanding and mitigating these failures is essential for a reliable warning preparedness.
- The impact of unofficial warning channel (at P_d = 68%) is more prominent during 'electricity failure' by increasing warning level by 8.9% when average increase in all cases was 7.2%

- Based on the ‘number of first neighbour warned houses’ (FW) as KPI, the impact of unofficial warning channel was almost equally prominent in ‘technology failure’ and ‘electricity failure’.
- When the official channel coverage is near half (40-50%) of its average coverage, the role of unofficial channel is more prominent, leading to increase in the warning level by about 18%. When the level of coverage with only official channel is of the order of 50%, these additional households warned could be vital in reducing fatality during a catastrophic evacuation situation.
- When the official channel coverage is outside the optimal range (i.e. <40 and > 50%), then the impact of unofficial channel diminishes in a non-linear fashion. The cross-section of the frontier curve is concave.

Having a customisable simulation experimental test bed like the ABM enables the ability for EMAs to study uncertainty in household warning behaviour on warning dissemination. This simulation model also provided a platform to quantify the impact of various official channel failures on overall dissemination and particularly the role of unofficial channel in the same. The experience of developing the model in two phases (prototype and city scale) not only increased the accuracy but also highlighted the interpretation of results from different scales. The methodology adopted in this thesis is a contribution to the OR/MS literature in the class of behavioural simulation models and also to evacuation modelling practise. The uniqueness of the proposed thesis is in the demonstration of quantifying household informant to neighbours behaviour. Apart from physical proximity (neighbours), a household could have other forms of social networks like friends, family, etc within the evacuated area and beyond. The role of social network (including and beyond neighbours) in warning dissemination is an interesting problem for further research. With wide spread use of internet as a warning tool and social network in the electronic media (Twitter, Face-book, blogs etc.) as a warning channel adds another dimension to the warning system.

Any model is an abstraction of reality, and the information lost due to assumption and implications’ limits the generalisability of the findings. The thesis focused on the residential household evacuation, and the warning dissemination to the commuters and transient population have been excluded from the model as a simplification. Apart from residential population, the transit population, commuters and family with visual and hearing disability are more vulnerable groups and EMAs need to make additional/specialised targeted preparedness for each of these vulnerable groups.

Only single dwelling household units were treated as agents and no distinction has been made for high-rise buildings. In reality, there are multiple dwelling units (like apartment complexes) and the warning dissemination within and across the neighbouring household will have much complex behaviour and is an interesting problem for further research. High-rise buildings have larger population density per unit and missing one building could mean 100s of evacuees. EMAs need to encourage the building associations to have internal evacuation warning plans and train evacuation wardens per building. For example,

- If one of the resident house (agent) in the high rise received warning message by any means (official or otherwise), they could trigger their internal fire alarm to signal an emergency situation.
- Whenever an internal speaker is available in the communal areas in each floor (e.g. lifts, parking spaces, etc) it could be used by the wardens to alert the households within their building.
- Within the evacuation plan, warning agency must have contact details of security staff of these buildings to make them single-point-of-contact (SPOC) for warning dissemination. During midnight, if none of the houses are warned, such a SPOC system can trigger onset of warning dissemination.

ABM needs various parameters for the planned city. Household level time-activity budget, channel capabilities and the warning dissemination curves for different times of the day are needed for customising these models to any other city. With the advent of new warning systems with faster dissemination capabilities, the empirical estimates used in the model need to be obtained for the city under planning. Only four activities are considered while adjusting the warning channel availability. Siren alone can alert on an emergency but cannot be a warning system unless the public are trained to interpret it.

Keeping aside these limitations of the model, EMAs could obtain the following learning based on the ABM simulation experiments. Warning dissemination during noon is vulnerable for the evacuating resident population. The maximum impact of unofficial channel could be about 18% when the official channel coverage is within optimal range (40-50%). With increase in official channel coverage, the neighbour informing behaviour has diminishing impact.

Level of warning coverage will indicate how many houses will possibly respond to the orders. In a household level, a delay in the warning will lead to delay in mobilisation and departure from the house. The role of warning dissemination (ESF-1) will have cascading impact evacuation traffic (ESF-2) which is generally managed by transport authorities. This entails a need for multi-agency collaboration possibly through an integrated approach to simulating evacuation (onset to safety) with evidence-based preparedness.

CHAPTER FIVE: MODEL DEVELOPMENT - EVACUEE TRANSPORT MANAGEMENT

5.1 **Evacuee transportation management – An Introduction**

During the Hurricane Katrina evacuation of New Orleans (2005), around 1 million people were evacuated with "*up to 100,000 people of New Orleans in the US had no access to transportation and would have to remain here. An estimated 20,000 would go to the Louisiana superdome designated as the shelter at last resort*" (Tate 2010). The role of transportation becomes very critical in ensuring the safety of thousands of lives during large-scale disasters. This chapter focuses on the traffic management of the evacuees moving from 'the place of danger to a place of safety'. The first section presents the ERGO findings from the interviews and data collection process followed by the proposed model for managing traffic, illustrated using the ERGO city case study.

5.2 **ERGO project findings on Evacuee transportation management**

In all the ERGO countries, the transport authorities were included at the planning stage as well as during evacuation response. The impact of the type of disaster (e.g. rising tide, rapid-onset disasters) on the time available for evacuation will have a direct bearing on the transport system. In 'rapid-onset' disasters, the role of traffic management is very critical. For example, glacial flooding in Iceland is caused due to the flow of erupted volcanic material over the glacial ice causing flood "*within one to two hours*" (Gudmundson 2008). In the case of tsunami threat in Japan, the time available for evacuation is even shorter. Depending on the distance of the resident population from the disaster epicentre, the time for completing the evacuation could be as short as one hour or less. This would require the EMAs to provide timely warning dissemination and manage traffic efficiently to facilitate a quick evacuation of everyone in the endangered areas. The following sub-sections summarise the key findings related to evacuee transport management which are grouped into three categories, namely: macro-level transport policies in the evacuation plan, policies related to evacuee destination and means of transport during evacuation, and use of models in evacuation traffic management.

5.2.1 Macro-level transport policies in the evacuation plan

A 'transport operations centre' was available in all the participant countries at different level of sophistication. Its usage during exercise and training for evacuation was explained during the ERGO visits. Transport officials who man these operations centres on a day-to-day basis were involved in the evacuation planning and preparedness. This facility has been used to provide live traffic updates to the decision makers during evacuation, and the same has been used for training and exercise. Transport officials collect traffic volume data also referred as 'origin and destination' (O-D) data for their day-to-day operations to monitor the traffic volumes. There is potential for using the O-D data to understand the potential volume of traffic for different times of the day. The 'O-D' data and analyses of 'traffic volume' could be included in the evacuation plan. As the public commute between residential areas and commercial districts in different times of the day, this O-D data will prove to be critical for identifying potential traffic volumes in the transport network. Transport authorities could identify traffic management strategies for different times of the day and test them using a simulation model to identify the most effective option.

As there are many 'means of transport' (e.g. buses, underground and over-ground metro, rail services) in large cities, there is a need for coordination among these authorities to provide needs-based distribution of resources. During the ERGO interviews, it was found that the umbrella transport agency in London, 'Transport for London – TFL' included a fulltime 'emergency planner' who would foresee the coordination of different service providers during day-to-day emergencies as well as during preparing for large-scale evacuation. Having such a staff to ensure inter-agency coordination in the evacuation planning and response may prove to be crucial during evacuation.

Transport officials in Germany use planning estimate of 'public transport usage during evacuation' to be 35% (all others are assumed to evacuate using cars). The transport authorities in Germany have identified bus stops to serve as evacuation 'pickup points', and this has been communicated in advance using billboards, preparedness leaflets and special symbols in the bus stops. A similar system was available in Japan as well. Denmark officials have also identified 'meeting points' for evacuees to board buses for evacuation. Having identified pickup points will provide flexibility for the transport authorities to operate 'special evacuation routes' for buses as well for the evacuees to know where to wait for transport support.

Iceland traffic police did not observe any 'panic behaviour' during the preventive evacuation for Mt. Eyjafjallajokull eruption-related glacial flooding. An evacuated interviewee, who lives about 20 km from the Eyjafjallajokull eruption site, said that she was normal and not panicking, and also that as a precaution, the car driving speed was slightly lower than usual. Through the preparedness leaflet, she knew the 'nearest shelter location' prior to the evacuation. The emergency officials had prepared in advance the evacuees in the Hollsvollur region using preparedness leaflet. Both the emergency officials and the evacuated public have cited the preparedness initiatives including the leaflet, information meetings and exercise as the key reasons for successful evacuation. The leaflet for the Hollsvollur region (Figure 5.1) provides information about:

i) glacial flooding path for that region
ii) potential inundated areas
iii) evacuation routes
iv) road closure points
v) Emergency aid centres.

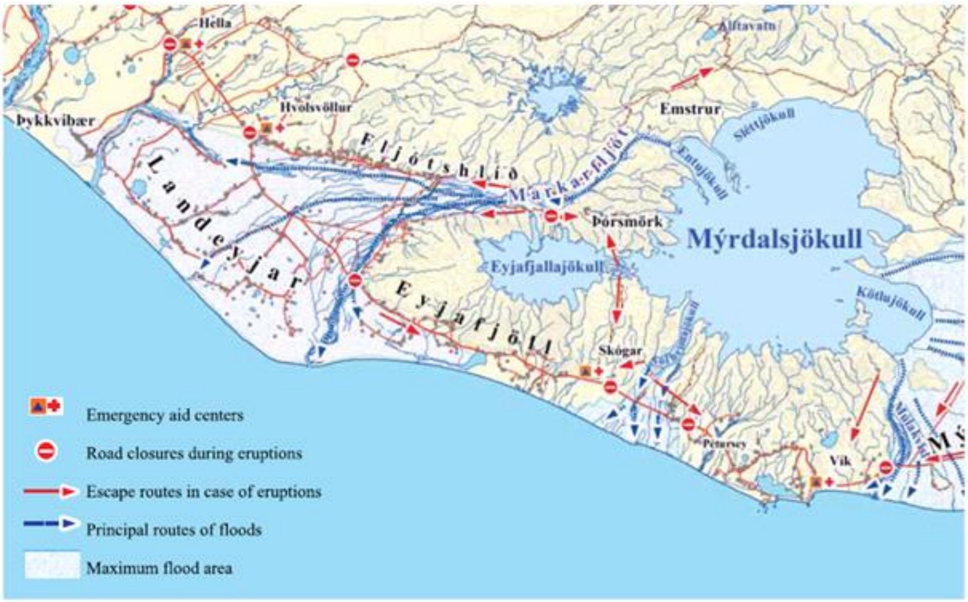


Figure 5.1 Screenshot of the 'Evacuation preparedness leaflet' distributed to the public in Hollsvollur region, Iceland

In the evacuation plan for the Hollsvollur region of Iceland, the EMAs have taken 25-30 minutes as the 'evacuation preparation time' or 'mobilisation time' (time between receiving the warning message and beginning to evacuate). Supporting this leaflet, the officials had shown the simulation model of flooding during 'information meetings' to the residents of the area prior to the event. The interviewed evacuee stated that showing the glacial flood simulation model to the evacuees residing in the area, helped them in understanding the time available for a potential flood to reach the zone and then heightened their risk perception.

In Japan, EMAs were using the 'Tokai-Tonankai-Nankai' earthquake as a planning scenario for large-scale evacuation that is expected to impact about 6 million evacuees and an estimated death of 250,000 (Chen et al. 2009). The Tokyo metropolitan authorities have a policy that the evacuation will be by foot and the evacuees will choose 'in-sheltering' (vertical evacuation – moving to higher floors within the building) and only as a last resort will go to the shelters within the zone. The use of cars during the evacuation is legally forbidden in some areas. On the other hand, Iceland, with a highly dispersed population, has a transport policy that the evacuation is only by cars as it is not feasible to send buses to the evacuation regions when the time available for evacuation is very short (in the order of a couple of hours). The authorities in Germany also believed that the proportion of car users will be high as it is one of the valued possessions.

During the Jutland fireworks accident in Denmark, about 750 houses with 2000 people were evacuated, with about 22 dead in the incident. In the first stage of evacuation, the authorities decided to evacuate 500 m around the factory. When the situation worsened, the danger zone was expanded to 1.5 km and the second stage of evacuation was needed. The railway lines were closed due to safety concerns. In a large-scale evacuation, closing of a public transport system, for example a railway line, will have an impact on the capacity available for the public and hence affects the ET. Along with evaluating their transport policies, the EMAs could identify such scenarios and then test using simulation models as part of preparedness initiative.

5.2.2 Policies related to evacuee destination and means of transport during evacuation

During the ERGO interviews, it was found that shelter use is the last resort as a destination and the evacuees would prefer to go to friends and family, and private accommodation. This confirms the findings on evacuation destination found in the published literature. Iceland has used behaviour studies to improve risk perception, as well as for obtaining a planning estimate for shelter needs. Belgium's medical service authorities believed that 5-10% of the evacuees will require sheltering, and this information could be used to estimate the traffic volume to different exits out of the evacuated area. Sweden had collected post-evacuation reports as well as research literature related to evacuation. As highlighted in the literature review section, the EMAs could use post-evacuation reports, stated-preference surveys, exercises, experience of the officials and social science literature to identify various destination preferences and devise traffic management plans accordingly. The choice of destination will impact the direction of traffic as well as subsequent evacuation support services like providing 'public transport support' and 'emergency accommodation'.

Transport authorities need to have planning estimates of the means of transport (cars, pedestrians, and public transport) in the evacuation plan in order to identify the demands for transport infrastructure. During the ERGO project, there were diverse plans about the 'means of transport' used during evacuation.

i) In Iceland, the ownership of cars is high and during the ERGO interview it was found that vehicle utilisation during evacuation was assumed to be 100% in the evacuation plan.
ii) In Belgium, when people do not own cars, it was planned to provide buses from pickup points around the inner zone around the Doel Nuclear plant evacuation.
iii) In the United Kingdom, Transport for London will run buses through normal bus routes as evacuation routes. This will reduce confusion among commuters who can take their normal bus routes during evacuation and help the bus drivers who know regular routes very well.
iv) Transport authorities in Germany will run buses along 'special evacuation routes' through pre-identified 'pickup points' in different flood inundation zones.

These different policies demonstrate diverse response options used by the transport authorities based on different priorities. The transport authorities in all the ERGO countries have formed collaboration with the neighbouring counties as well as with the private bus operators to support additional vehicle demands during evacuation. In Iceland, information about road traffic conditions was updated using a website as well as the information hotline number 1777. Electronic billboards were widely used to provide live updates to the evacuees in the ERGO countries.

5.2.3 Use of models in evacuation transport management

Iceland has developed 'simulation model of evacuation using cars' which was used to estimate the ET for glacial flooding due to Mt. Katla eruption. This simulation model was developed in-house using ABM technique. Here, cars were represented as agents with pre-specified driving behaviour (e.g. acceleration, braking, and distance from other cars). The evacuation plan of Iceland also assumed that the evacuees need a 'mobilisation time' (defined as the time between receiving the warning message to leaving the house) of about 30 minutes, and this time has been included in the model. 'Traffic loading points' (points at which traffic will feed from minor roads into major roads) were identified for each evacuation zone. The authorities have also identified the evacuation route for each zone and then communicated it in the leaflet. Figure 5.1 is a screenshot of the 'eruption emergency guidelines' leaflet distributed to the residents living in the Hollsvollur region of Iceland for glacial flooding.

The traffic simulation model developed in Iceland was used to obtain a planning estimate of the ET and this has been modelled as a two-step process, namely the first stage being evacuating from the house to the nearest 'traffic loading point' and the second stage is to drive in car from the traffic loading point to the nearest exit. This model was found to be helpful for the emergency officials to prioritise evacuation for different zones and test the chosen evacuation route. This model was primarily used to obtain a planning estimate for TET and to identify bottlenecks in the road network. The authorities also presented the model to the public during information meetings in order to raise their awareness. Iceland has also conducted risk assessment at the community level and then used the simulation model to prioritise the evacuation based on the expected time when flood will reach each community.

In Sweden, the authorities in Uppsala County have used 'Plume Behaviour models' to prioritise the evacuation of inner zone (12-15 km) around the nuclear power plant. During an exercise it was found that 40 minutes was enough to warn everyone in the inner zone using official channels as well as the special radio alarm system. The evacuees will be leaving using car as well as using buses from key locations in the zone. The model is used to obtain ET.

In Japan, the emergency officials have developed a model for underground station evacuation in Japan using multi-agent simulation. Another ABM was developed for traffic management around 'Disneyland Tokyo' in order to test traffic routing. During the interview, it was found that EMAs in Poland also use models for evacuation transport planning. Moto Grand Prix in Spain is an annual event that attracts people from around the world. The authorities managing the event have used a traffic simulation model to test exit routing plans, including contra flow initiatives, along with a field exercise. This model was used for egress simulation after the event as well to support evacuation plan.

Anna Bligh, the premiere of Queensland Australia announced that "*No-one should be leaving home now*" (Daily Telegraph, 2011) during the 'Cyclone Yasi' evacuation in February 2011. Though there is no information about the use of traffic model in this particular decision, to make such a decision with confidence - "*whether to stop evacuation or allow for few more hours*" - would involve combining the disaster prediction models (in this case cyclone model) with the transport management models (which will give an estimate of expected ET). A delayed departure of the household might expose them to the threat and make them unsafe. The readers are reminded that during Hurricane Rita (2005) *"110 people were killed in the evacuation, compared to only nine in the storm"* (Leonard 2008). Computer models combined with live update on traffic conditions will play a critical role to support evacuation decision makers to know 'how long to delay the evacuation order' and even 'whether to stop the evacuation' particularly during preventive evacuations.

5.2.4 Research gaps on planning for ESF-2

The findings from ERGO interviews highlighted diverse transport policies as well as diverse planning basis for transport management. The interviews also identified some of the transport models used among the ERGO countries. Similar to the 'stated preference evacuation behaviour studies' conducted by FEMA in the United States, it was found that such studies have been used by the EMAs in Iceland in collaboration with the academic community. There are two major findings based on the ERGO interviews and literature reviews.

First, since there was no integrated system that covered all phases of evacuation, there is scope of using a model for integrating the transport network, evacuee behaviour and response strategies in order to evaluate 'evacuee transport management' as a part of preparedness initiative. Second, as different households receive warning and respond at different points in time, a realistic estimation of overall ET need to factor the warning time. EMAs need a platform to test their planning assumptions as well as to identify response strategies. Inline to these observations, this thesis will propose an evacuee behaviour-based transport management model.

Iceland's car simulation model accounts the car driver behaviours and was found to be very helpful. For EMAs there are additional modes of transport and traffic management strategies that are available to the planner. This could be tested in advance using a computer model. Simulation models, known for the richness of experimenting different scenarios, can provide the transport planner more confidence in their response choices. The following section presents the overview of the model used for managing evacuation traffic. The capabilities of such model will be illustrated by using the ERGO city case study. The aim of this model is to help the transport authorities to obtain planning estimates for ET and its impact on various response choices. The model has been developed by combining network modelling approach with ABM.

5.3 **Model for 'Evacuee transport management' – Description**

This chapter on the 'model for evacuee transport management' (ESF – 2) covers the evacuation phase between 'household receiving the warning message' and 'until they reach a place of safety'. Once the household receives the warning message, they will require some time to prepare for evacuation (referred to as mobilisation time) before departing. A delay in the warning message can have a cascading effect on the 'departure time' and hence the 'time to reach safety'. Evacuation is complete only on the evacuees reaching their chosen safe location.

An ABM is proposed in this thesis to study the household behaviour during transportation phase (ESF-2), given the level of warning dissemination scenario from ESF-1. Agents and agent behaviours are key components of ABM transportation model. The general principle of implementing key components is presented in Section 5.3 and the illustration using ERGO city is presented in Section 5.4.

There are two classes of agents in the ABM transportation model: 'household agents' and 'vehicle agents'. Each household is represented as an 'agent' and the household level behavioural choices prior to their departure are set as behavioural rules for the agents. Vehicles in the model, namely cars and buses, are another set of agents that represent the household physical movement from the evacuated zone (origin) to the chosen destination.

There are two set of behaviours relevant to ESF-2 namely 'household behaviour' and 'vehicle driving behaviour', which maps to the two classes of agents. Sections 5.3.1 to 5.3.4 describe household agents' evacuation decisions and its implementation in the ABM. Section 5.3.5 describes the modelling of vehicle agents' movement in the road network.

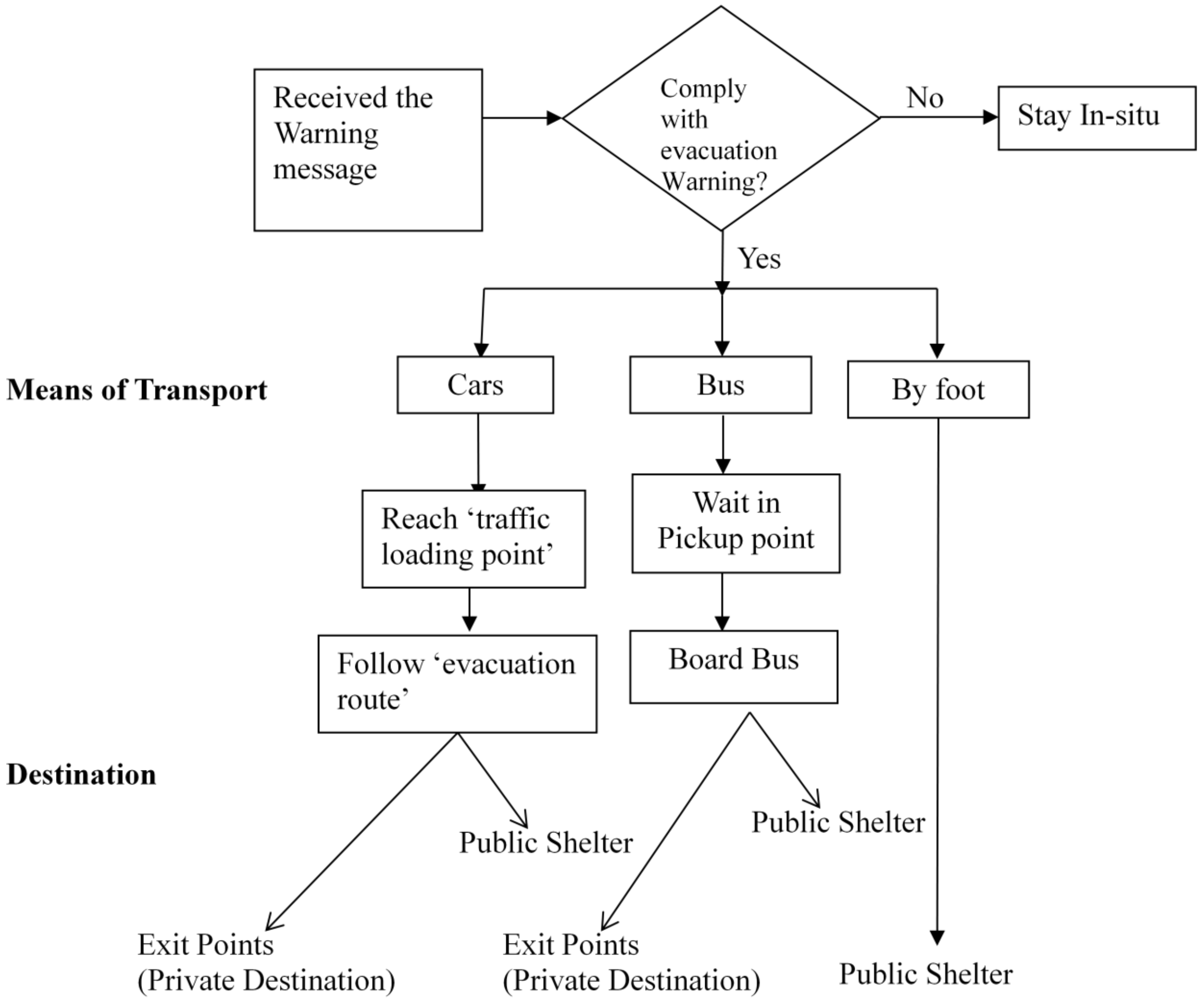


Figure 5.2 Household's evacuation transport choices

After receiving warning message, some of the houses may not comply with the 'evacuation order' and hence may stay in situ risking their lives. Figure 5.2 summarises the household level transport behaviour choices. For an evacuating household, there are four major choices made prior to leaving the place of danger:

- Destination (Where to go?)
- Means of transport (How to go?)
- Evacuation route (Which roads to take?)
- Departure time (When to leave?)

5.3.1 Evacuation destination

There are two major groups of destinations indicated in the transport model namely 'public shelters' and 'private destinations'. In general, the shelter authorities (ESF-3) estimate the level of shelter usage and also location of shelters. 'Public shelter' provided by the authorities is one destination group and the shelter information is needed for transport planning. 'Private destination' (e.g. family, friends and private accommodation) is represented in the model by various exit points in the road network. In general, destinations are discrete points in the evacuation network that attracts traffic volume towards it and acts as a 'sink' for vehicle agents during simulation.

First, a household decides whether they want to move to public shelter or otherwise. In general, a house may pick a nearest, a close-by shelter or randomly any shelter based on their personal preference. A 'shelter choice set' is a discrete set of shelter-ids for each zone comprising of shelters in the vicinity and few random shelters. For households deciding on shelters, they select one from 'shelter choice set' as their destination. Detailed discussion on shelter choice behaviour is presented in the next chapter (ESF-3).

In the literature, the choice of 'private destination' is influenced by various factors (Southworth 1991, p25) such as 'closest exit points based on travel distance or expected travel time, personal choice (location of friends and relatives, speed of onset), as per evacuation plan and existing traffic conditions'. In this thesis, for each zone a set of exit points were identified based on the two classes 'closest exit points' and 'few random ones as personal choice'.

If a household chooses private destination, they will randomly pick an exit point from a set of exit points for their zone. O-D matrix provides the route between the household location (origin) and the chosen exit (destination). The household agent will query the O-D matrix and prepare a route plan. When evacuees reach the selected exit point (their sink), they are considered to be evacuated safely and treated to be beyond the scope of the transport model (i.e. they leave the system).

A model-based computation of outflow rate of evacuees for tsunami evacuation scenario was developed for the city of Padang using a micro-simulation model (Lammel et al. 2008). As key planning variables for shelter operations are the 'proportions of shelter users among all the evacuees' and 'the arrival time at the shelter', these were computed in this study using MATSim-based transportation models. The output of this model was used to obtain ET and outflow rate of evacuees from the inundated areas to the destinations. ABM provides a platform to implement household shelter choices as an agent's behaviour and study its impact on overall evacuation performance.

It is assumed in this thesis that, the household's decision of choosing a destination is appropriately represented using a simple heuristic of 'choosing from the ones in the vicinity'. This heuristic will aim at minimising effort in travelling to the shelter/private destination from the household perspective. Alternatively, an optimization model can be formulated to represent household level shelter choice making as illustrated by Kongsomsaksakul et al. (2005). This thesis argues that, it is unrealistic that every household may use a sophisticated optimization approach for shelter choice and hence a heuristic is better representing at the household level.

As the GOs in charge for allocating shelters will have information about the available shelters and estimated demand, such an optimization formulation is preferable from the GO perspective in order to arrive at 'system level (or overall) optimal solution' and issue a sheltering advice to evacuating zones. It can be observed that there is a need for integrated approach of 'coordination and information exchange' between EMAs managing ESF-2 (transport authorities) and ESF-3 (shelter providers). Chapter 6 that covers the ESF-3 presents such a model along with sensitivity analyses of household shelter choice behaviour.

5.3.2 Means of transport

The second choice to be made by the evacuating household is the 'means of transport'. A post-disaster report after Hurricane Katrina (Gutierrez 2011) found that, "*Katrina's evacuation plan functioned relatively well for motorists but failed to serve people who depend on public transit*". Transport authorities need to have an estimate of households using various means of transport in order to manage the evacuating traffic and also cater to public transport demands. In the model, three means of transport were modelled namely pedestrian evacuees, evacuation using cars and public transport using evacuation buses.

A multi-modal Agent-Based transport model is proposed in this thesis for evacuation transport management. Three modes of transport namely pedestrians, cars and evacuation bus have been modelled in this thesis. In reality, there are other context-specific public transport systems such as metros, underground rails and ferries used during evacuation. Even though these transport means are important, they do not add to the traffic in the road networks, which is used as the predominant evacuation means (i.e. cars and buses). As a simplification of

ABM 'the other means of transport' were not included in the model and are considered to be a problem for further research.

For households evacuating using cars, at the time of departure, a car agent will be created in run-time in the ABM. For each evacuation zone, a traffic loading point has been identified and a car will enter into the road network at 'departure time'. The number of evacuating vehicles per household and the number of occupants depends on the vehicle ownership (Southworth 1991) and time of the day (Southworth 1991, Wolshon 2006). A household holding more than one vehicle can use one or all the vehicles while evacuating. As a simplification, this thesis assumes that one car is used by the household to evacuate all the family members together.

Households evacuating as 'pedestrians' will reach their destination at time = departure time + travel time. The average value of pedestrian walking speed is used as 1.3m/sec. This walking speed is taken as a representative value from a cabinet office report of the UK (Cabinet-Report, 2009 p.19). Another study used 1.33 m/sec as pedestrian walking speed (Mas et al. 2012a). The travel time for pedestrians will be computed by multiplying 'walking speed' and 'linear evacuation distance from household to destination'.

The third means of transport for the household is by using public transport buses. A two-stage process is used to represent evacuation behaviour using buses.

v) Stage-1: On departure from house (place of danger), evacuees will move as pedestrians to the nearest 'pickup point' and will be in a virtual 'ordered queue' with FIFO policy (First In-First Out).
vi) Stage-2 Evacuees will board the bus as a family in the order of arrival at the pickup. Once the next bus is available at the pickup point (with vacant space), the evacuees will be taken to safety (destination) at the last bus stop.

Once the vehicles (bus and car) are on the roads, their behaviour is modelled using a widely used 'car-following' model principle and will be dynamically influenced by the existing traffic conditions, speed limit in the road and their evacuation route to destination. The behaviour of vehicle agents and its implementation is presented in Section 5.3.5.

5.3.3 Evacuation routes

At a household level, there could be various evacuation routes from their house to the chosen destination (shelter or private). Authorities provide 'planned evacuation route' and road closures in advance through preparedness leaflets. For example, Figure 5.1, a preparedness leaflet of Iceland glacial flooding evacuation, indicates the evacuation routes by arrows. Any real-time information on the route availability and closures are generally made available through media channels. Apart from following the evacuation route provided by the EMA, a household could choose a convenient, familiar or regularly used route for evacuation. In this thesis, a household on deciding its destination will use the shortest path to destination within evacuation routes.

For each traffic loading point and destination, a route-plan is pre-processed for the evacuation network, and a combination of these values is stored as route-plan matrix. In this thesis, the route-plan matrix is loaded as an input file. A similar architecture was used in the MASSVAC evacuation model. A route plan contains the order of junctions to be traversed in the road network from the origin (traffic loading point) to the destination (a shelter or exit point). At each household, a route plan is decided in the run-time at the time of departure from evacuation route-plan matrix. It is assumed that this route plan will not be changed further, as a simplification in the ABM.

5.3.4 Departure time

'Departure time' refers to the time when a household evacuates their residence and enters the evacuation model as a vehicle agent class based on '*means of transport*'. This household parameter is dependent on factors such as the time of receiving the warning message (warning time), personalising the threat and warning content, expected time of disaster impact/striking, preparation time (mobilisation time) for all the items to be carried, etc. There are four approaches specified by Mas et al. (2012a) for departure time. "*The departure times are generally determined by applying an exogenous response curve stating the percentage of departures in each time interval" (Pel et al. 2011, p5).* These response curves were assumed to follow various statistical distributions like uniform, Poisson and Weibull distributions.

"*Evacuation being disruptive and inconvenient, households often delays their travel decision until the threat appears imminent*" (Wolshon 2006, p28). This would lead to simultaneous late departures 'closer to the actual time when disaster strikes', risking lives during evacuation and enormous travel demand in a short period on transport infrastructure. Not all households receive warning message at the same time (refer to Figure 4.10 for a typical warning response curve), and hence houses depart at different points in time. A household may need time to inform their neighbours (unofficial channel) apart from preparing to leave, and the timeline was depicted in Figure 4.2 (defaulter) and Figure 4.3 (non-defaulter house). Departure time = Warning time + 'time to inform neighbour' + mobilisation time. As this thesis advocates an integrated approach for the three ESFs, departure response curves were developed for a specific warning dissemination scenario using the formula above. This thesis argues that in the absence of context-specific departure data, the computation of departure curve using warning curve provides a reliable estimate than assuming 'time series of percentage departures'. In this case, the accuracy of warning response data will affect the accuracy of departure data.

For transport authorities to understand 'when the evacuees will reach safety' (i.e. ET), it is important to understand 'when a household will depart' and the dynamic interaction of evacuating vehicles in the evacuation road network. The household's 'warning received time' is obtained from the output of warning dissemination model (ESF-1). An estimated 'mobilisation time' is added to the household's warning time. In this thesis, 25 minutes is considered as a constant mobilisation time for household. This value is comparable to the evacuation plan for the Hollsvollur region of Iceland where the EMAs used 25-30 minutes. The departure time is set as an agent parameter (household) at the setup stage of the model. At the departure time, a household flag is set to indicate the onset of evacuation and a new vehicle agent is created for the house.

5.3.5 Modelling driving behaviour

During the ERGO interviews in Iceland (2010) after the preventive evacuation for Mt. Eyjafjallajokull glacial flooding, an evacuee shared that 'she was following the traffic rules and her driving was cautiously slower than usual speed'. While developing the evacuee transportation model, this thesis assumed that the evacuating drivers will follow the traffic rules. In reality some of the drivers may panic during evacuation and disobey traffic rules and others may have rude driving behaviour. Such behaviours are realistic and yet no generalisable empirical evidence exists on the per cent drivers showing rude behaviour. A rude driving behaviour can cause delay in the evacuation and endanger other road users; this requires further research on incorporating into the transportation model in order to study the potential impact of driving behaviours. This thesis is limited to 'normal compliance driving behaviour' and the following paragraphs present the modelling of behaviours.

Household evacuation decisions as elaborated in Sections 5.3.1 to 5.3.4 are 'travel choice behaviours' independently made at each household. Once the household departs, a vehicle agent is created in the model; its interaction with other vehicles during evacuation travel in the transportation network is influenced by driving behaviours. For a leader follower pair, the leader influences the following vehicle's state (new speed and distance to move) by its current speed and the gap/distance between them. Driving behaviour modelling predominantly focused on predicting movement of vehicles as a function of speed and distance of the predecessor. Car-following models provide the logic for computing the following vehicle's state at each tick and readers are referred to Ossen and Hoogendoorn (2011) for a detailed comparison of car-following models. The literature review showed that the most of car-following model theories used equations with parameters requiring calibration. This thesis has adopted 'desired speed' and 'safe gap' as two parameters for building a single-lane car-following model using simple conditional rules. As evacuation involves simultaneous loading of a large number of cars into the network, the speed and the distance between the cars to avoid collision is of more of a priority in single-lane traffic.

Evacuating vehicles' behaviour in the evacuation network forms the crux of the transportation models. "*Drivers may behave hasty or anxious during emergency conditions, causing their driving behaviour to change drastically*" (Tu et al. 2010, p68). This study modelled parameters such as acceleration rate, maximum speed, minimum gap distance and minimum headway for modelling driving behaviour. Here, "*mean headway is the time in seconds from the front of the vehicle following (current vehicle) to the rear of the vehicle in front, excluding the time that the following vehicle travels*" (Tu et al. 2010, p71). Though some drivers might drive rudely during evacuation, normal compliance driving behaviour is often used in transportation models (Pel et al. 2011).

'Vehicle/car-following model' provides logic for the movement of vehicle in every simulation time step. In the proposed ABM there are three types of vehicles such as Cars, transient vehicles and buses. Transient vehicles volume refers to regular motor way users who are not part of evacuating population. All these vehicle agents have two 'behavioural attributes' representing the driving behaviour namely desired driving speed and perceived safe gap.

Desired Driving speed

In this thesis, 'desired speed' is defined as the top speed that the driver aims to achieve and maintain throughout the journey. The desired driving speed is unique to each driver and this uncertainty is represented by using an additive component in excess of the driving speed. Driver attributes such as age, gender, etc can influence the driving speed. However, these micro-attributes of evacuees though important have not been considered in this thesis.

The aim of the vehicle agent is to accelerate/decelerate its speed to match the 'desired speed' depending on the condition of the road traffic. This desired speed parameter is set at the initialisation/departure stage of the evacuation. As this parameter is unique to each driver, the value is obtained by combining a deterministic component (average desired speed) and uncertain component (random within a range). It is assumed that the randomness of desired speed values can be represented using a random normal distribution.

Perceived safe gap

Perceived safe gap is a driver's attribute that indicates the linear distance ahead in the road where any vehicles' behaviour will have influence on the movement decision. A leader is the nearest car within the perceived safe gap for a vehicle. This gap is needed to avoid collision with the next vehicle ahead. In each time step, a car needs to decide on the distance to move and also adjust the speed.

A crowded condition for car movement was specified as two cars in a 5m x 5m grid (Mas et al. 2012a) and this allows approximately 1 m gap between cars when the car-size is taken as 2m. Contrary to the traffic movement on normal days, during evacuation there will be high volume of vehicles (Wolshon 2006); the speed of vehicle is highly influenced by the existing traffic, and hence maintaining safe gap would be of more priority for the drivers than maximising the speed. A minimum safe gap is large enough to suddenly stop a vehicle when the leader stops in the next time step and avoid collision. After maintaining the safe gap, a vehicle will adjust its speed to reach the desired speed.

These two parameters are initialised for each agent using the relation below:

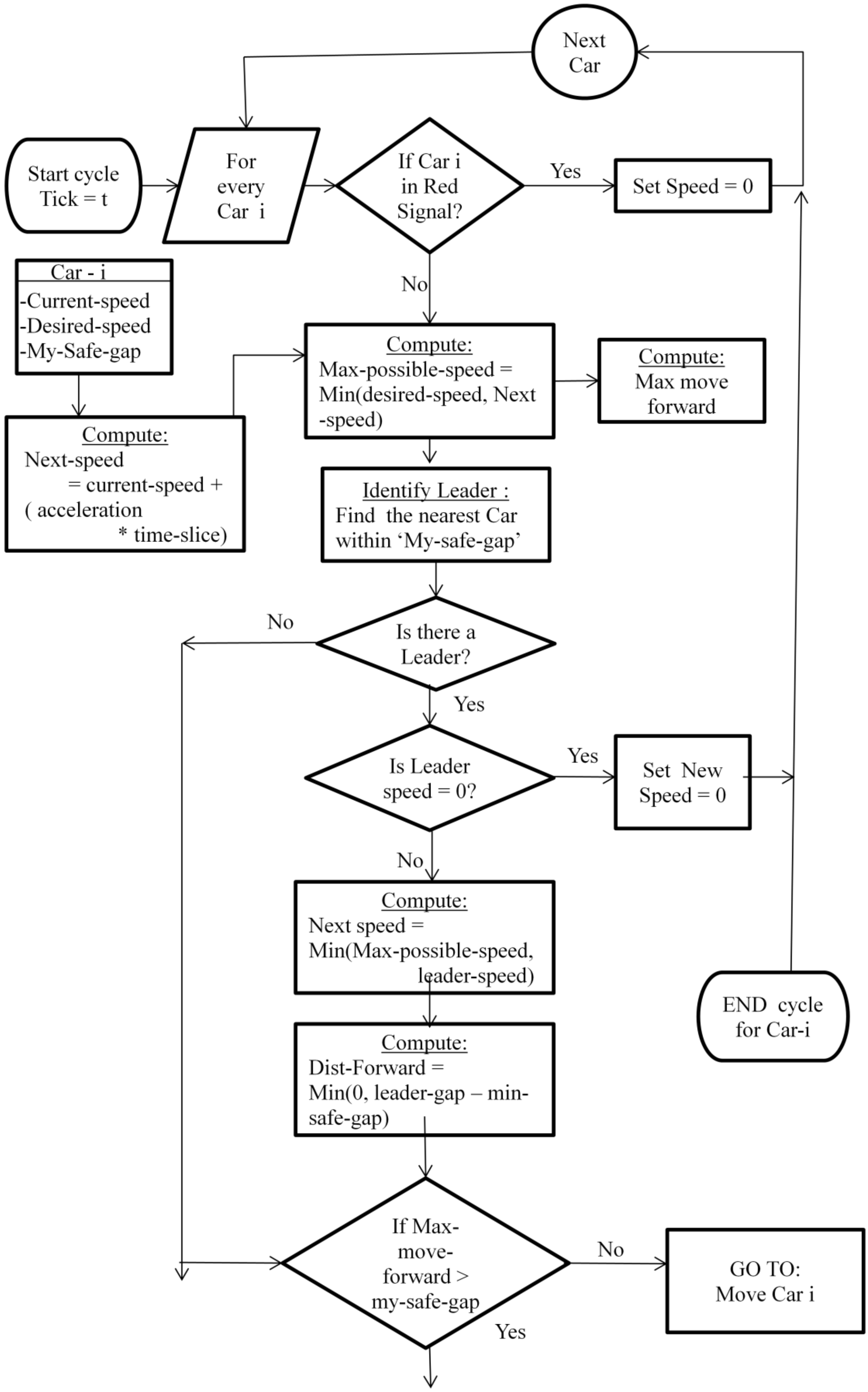
- Set ‘Desired speed’ = Average desired speed + uncertain speed component
- Set ‘perceived safe gap’ = Average safe gap + uncertain safe gap component

Driving behaviour rules

The current speed of the vehicle is adjusted using the ‘car-following model’ with simple conditional statements. When there are no vehicles ahead (within ‘perceived safe gap’), the vehicle always desires to maintain its speed to be the ‘desired driving speed’. If there are vehicles ahead, the vehicle will alter their speed to set a minimum of {current speed of vehicle ahead, desired speed}. Apart from the vehicles, the traffic signals can influence the movement of vehicles. If there is a traffic signal ahead, the vehicle proceeds only when it is green. These behavioural attributes are used in car-following model in deciding the speed and distance covered in every simulation time step (called ticks).

Car-following models

There are various car-following algorithms formulated in the literature, and readers are referred to Ossen and Hoogendoorn (2011) for a summary and comparison. This thesis argues that the drivers would aim to minimise the gap with the leading vehicle and never fall below a minimum safe gap to avoid collision. The speed of the vehicle is maximised subject to maintaining the minimum safe gap. Advances in surveillance technologies enable the transport planners to collect vehicle tracking information using trajectory data and further use in car-following models (Zheng et al. 2012). Lansdowne (2006) computed the speed of the vehicle based on safe-gap and max-speed possible. A car decides to set its speed to a minimum of these and then move its current position in the time step The simplified approach adopted in this thesis requires only three major sets of data car size, speed and safe gap, and is relatively less expensive to obtain for adopting the approach to any other city. Figure 5.3 represents a flow chart of the car-following logic that will be executed for every car for every tick. Figure 5.4 presents the code snippet of car-following logic implemented in this thesis. For households evacuating using cars, the event flow from ‘departure to destination’ is presented in the next sub-section.


Next Car
Start cycle Tick = t
For every Car i
If Car i in Red Signal?
Yes
Set Speed = 0
Car - i
-Current-speed
-Desired-speed
-My-Safe-gap
No
Compute:
Max-possible-speed = Min(desired-speed, Next -speed)
Compute:
Max move forward
Compute:
Next-speed = current-speed + (acceleration * time-slice)
Identify Leader :
Find the nearest Car within 'My-safe-gap'
No
Is there a Leader?
Yes
Is Leader speed = 0?
Yes
Set New Speed = 0
No
Compute:
Next speed = Min(Max-possible-speed, leader-speed)
END cycle for Car-i
Compute:
Dist-Forward = Min(0, leader-gap – min-safe-gap)
If Max-move-forward > my-safe-gap
No
GO TO: Move Car i
Yes

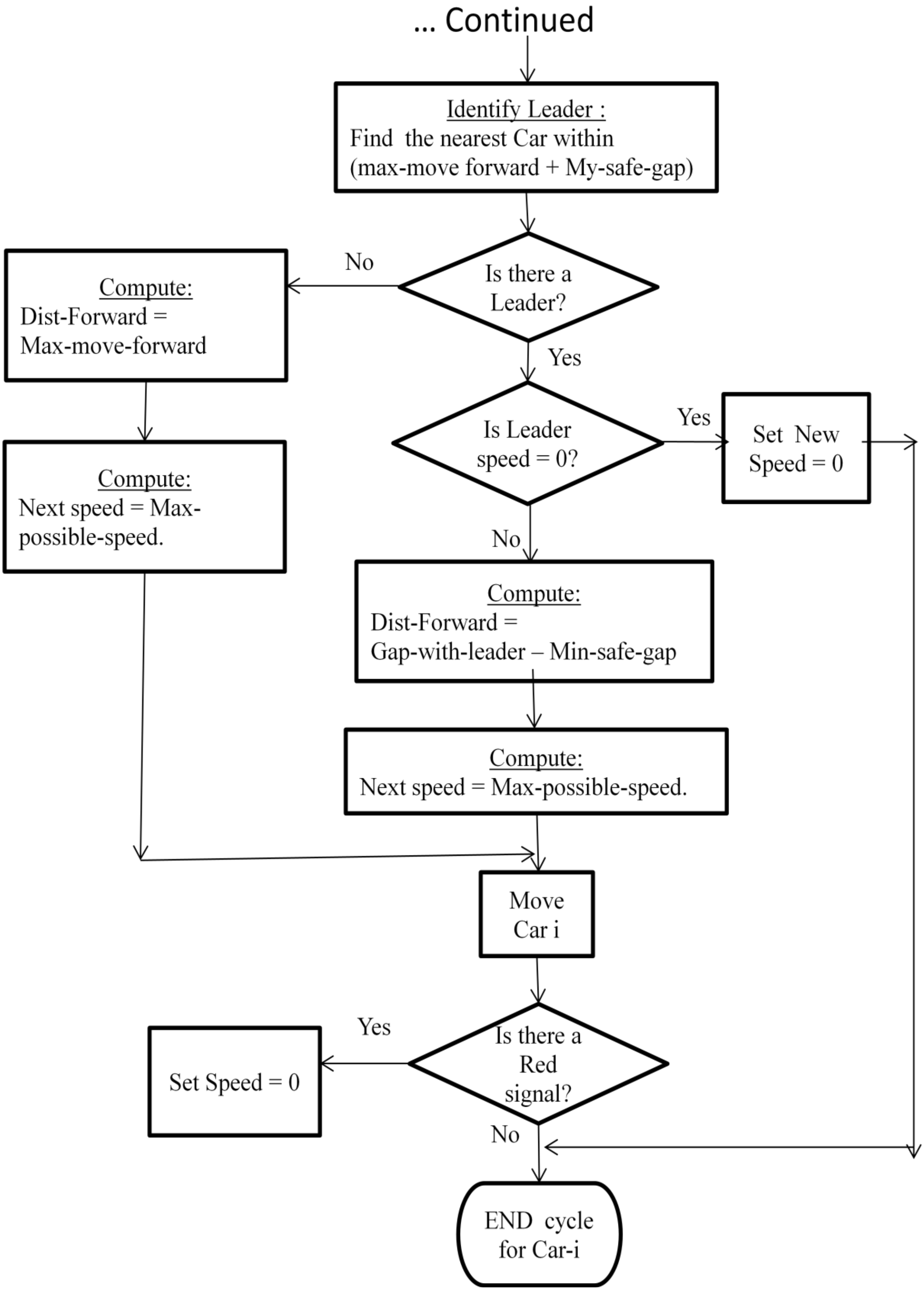


Figure 5.3 Flow chart of the 'car-following model' implementation

```
to Car-following-Module
  let proc-name "Car-following-Module"
  ;;Check who is the nearest car ahead
  let my-safe-gap 0 let my-id 0 let new-speed 0
  let current-road-limit 0
  let my-max-next-speed 0 let max-movement 0
  let my-speed 0 let leader-id 0
  let dist-forward 0 let leader-gap 0
  let junc-ahead-free false
  let any-cars-at-junction false
  ask cars with [(self = myself)] [
                      set my-safe-gap PERCEIVED-safe-gap
                      set current-road-limit road-speed-limit
                      set my-id who
                      set my-speed speed
    set my-max-next-speed Min (list (my-speed + (acceleration * accl-mpsec2-to-kph2 * tick-to-hour))
                                desired-speed current-road-limit) ;; kmph
    set max-movement (my-max-next-speed * speed-kph-to-patchpertick  ) ;; units in patches
   ]

  ;show (word "Clock " ticks "My id is " my-id "Xcor,Ycor: " xcor ", " ycor " My-speed: " my-speed " My-max-next-speed "
  let nearest-car-ahead min-one-of cars with [(self != myself) and (final-dest = false)]
                                           in-cone (my-safe-gap ) 30 [distance myself]
  ;show (word "Clock " ticks "My id is " my-id " " "Who is the nearest car " nearest-car-ahead )
  ifelse nearest-car-ahead != nobody ; R1
  [ ; show (word proc-name " car-id:" my-id " R11" ) ; R11
    ask nearest-car-ahead [ Set leader-gap (distance myself) set leader-id who]
   ;; if there is another car ahead within my perceived safe gap.
    ifelse ([speed] of nearest-car-ahead) < 1 ;; R2 This is needed when current location is closer to traffic signal
      [; show (word proc-name " car-id:" my-id "and my leader" leader-id " R21" )  ; R21
        set new-speed 0
      ] ;; R21
      [; show (word proc-name " car-id:" my-id "and my leader" leader-id " R22" ) ;;R22
        set dist-forward (leader-gap - MIN-SAFE-GAP)
        ifelse (dist-forward <= 0)
```

```
          ifelse (dist-forward <= 0)
            [set dist-forward 0 set new-speed 0]
            [set new-speed ((dist-forward * PATCH-UNIT-LENGTH / 1000)/ (TIME-SLICE / 60))]
        ]
    ]
    [ ;; if there is NO car ahead within my perceived safe gap.
      ; show (word proc-name " car-id:" my-id " R12" )   ; R12
      ifelse (max-movement > my-safe-gap) ; R3
      ; if  (max-movement > my-safe-gap) ; R3
        [ ; show (word proc-name " car-id:" my-id " R31" ) ; R31
          set nearest-car-ahead min-one-of cars with [(self != myself) and (final-dest = false)]
                                                 in-cone (my-safe-gap + max-movement ) 30 [distance myself]
          ;; Checking for any car within (my-safe-gap + max-movement) helps in "always"
          ; maintaining minimum gap (i.e. min-safe-gap)
          ifelse nearest-car-ahead != nobody
            [ ask nearest-car-ahead [ Set leader-gap (distance myself) set leader-id who]
              ; show (word proc-name " car-id:" my-id "and my leader" leader-id " R41" )  ; R41
              ;; if there is another car ahead within (my-safe-gap + max-movement).
               ifelse ([speed] of nearest-car-ahead) < 1 ;; R5 This is needed when current location
                                                         ;is closer to traffic signal
                  [; show (word proc-name " car-id:" my-id "and my leader" leader-id " R51" ) ; R51
                    set dist-forward (leader-gap - MIN-SAFE-GAP)
                    set new-speed 0
                  ]
                  [ ; show (word proc-name " car-id:" my-id " R52" ) ; R52
                    set new-speed Min list ([speed] of nearest-car-ahead) my-max-next-speed
                    set dist-forward (new-speed * (TIME-SLICE / 60) / (1000 / PATCH-UNIT-LENGTH))
                  ]
            ]
            [  ;show (word proc-name " car-id:" my-id "and my leader" leader-id " R42" ) ; R42
               ;; if there is NO car ahead within (my-safe-gap + max-movement).
               set new-speed my-max-next-speed
               set dist-forward max-movement
          ]
        ]
```

```
      ; When max-movement is <= perceived safe-gap, the logic to ensure anti-collision is taken care
      ; in taken care in R1 rule where it looks for any leaders within perceived safe gap.
      [; show (word proc-name " car-id:" my-id " R32" ) ; R32
        ;set dist-forward (max-movement - MIN-SAFE-GAP)
        set dist-forward (max-movement)
        ifelse (dist-forward <= 0)
            [set dist-forward 0 set new-speed 0]
            [set new-speed ((dist-forward * PATCH-UNIT-LENGTH / 1000)/ (TIME-SLICE / 60))]
      ]

  ] ; End of R12
```

Figure 5.4 Code snippet of car-following model implementation

Event Flow – Evacuation using cars

1. Compute departure time for the house using the formula

   Departure time = (warning time + assimilation time + informal warning time + Mobilisation time).

2. When simulation clock = departure time, set departure-flag property of household agent as 'true'.
3. Create a car agent and set the following agent properties
   a. Starting-time = departure time
   b. House-id = id of the departed house
   c. Location (x-y coordinates) = traffic loading point (x-y coordinates)
   d. Set 'heading' of the car = 'heading' in the patch below it.
4. Compute the time to reach traffic the 'traffic loading point' for that zone.
5. Enter the loading point after checking the following
   a. If the loading point is free and no vehicles on loading queue, then enter the network.
   b. If the loading point is free and there are vehicles in loading queue, then join the virtual queue and wait for entering into the network by FIFO policy.
   c. If the loading point is busy, then enter the loading point virtual queue.
6. Regulate 'car speed' at each time-step by repeating the following based on the changing traffic condition
   a. If there is a car ahead, progressively accelerate/decelerate the speed to match the car speed.
   b. If there is no car ahead, progressively accelerate the speed to match the top speed which is the minimum of 'road speed limits and desired speed'.
   c. If the 'car's speed' reaches top speed then maintain the same speed till the next.
7. Always maintain the minimum safe gap with the leader vehicle ahead.
8. Traverse to each junction in the route-plan.
9. On reaching a junction along the evacuation route, change the direction to the next junction. Update the 'next junction' in the agent properties.
10. Move towards the next junction along the evacuation route.
11. While traversing, if there is a traffic signal indicating 'red', stop the vehicle or join the queue of the vehicles ahead. Wait for the signal to turn 'green' and then proceed or follow the car ahead.

12. In summary, a car agent must regulate speed, move along the evacuation route and follow traffic signals.
13. Reach destination and update the 'destination arrival time' in the car agent properties. The car agent is hidden and will not interact with other vehicle agents.
14. Compute evacuation travel time = destination arrival time – departure time.

The event flow for transient vehicles and buses is the same as cars. The buses collect passengers from the pickup-points along route whenever there are vacant seats. For simplicity, the time needed for loading evacuees into the bus is taken as zero.

5.3.6 Modelling of urban evacuation road network

This thesis presents a multi-modal network-ABM evacuee transportation model in which houses and vehicles are agents, and the transport infrastructure is represented using network model. Evacuation using 'cars, public buses and as pedestrians' is modelled in this thesis. Movement of evacuating vehicles (agents) occurs in the road network. The objective of this model is to provide a platform for the EMAs to evaluate the household transport choices and the impact of transport policy on ET. This thesis advocates an integrated evacuation planning by understanding cascading implications of various ESFs on overall ET. The objectives of the proposed model are:

a) To study the level of impact of unofficial warning channel & warning performance on ET.
b) To model the impact of household behaviour in transport choices.
c) To adopt a model-based multi-modal transport planning of evacuating public.
d) To use analyses from model results for allocating evacuation buses.

There are various transport models available for mass evacuation planning, to name a few OREMS (Oakridge evacuation management system), TEVACS (Transportation evacuation systems), DYNEV, MATSim and MASSVAC. Summary of evacuation models was presented in the literature review chapter section 2.1. In general, these models use network modelling approach to identify the best routes (Cova and Johnson 2003, Chen et al. 2012) transport planning and study the congestion during evacuation (Kwan and Ransberger 2010). In line to these models, the ABM transport model will use 'network modelling' principle to represent the road network.

Basic building blocks in a 'network modelling approach' are arcs and nodes. In the network modelling approach,

- Roads are represented by 'arcs'. Lanes and directions of the road (as a heading angle 0 to 359 degrees) are represented as properties of the arc.
- 'Road junctions, bus pickup locations, traffic loading points (i.e. location where a 'vehicle agent' enters into the model road network), traffic signals, shelters and exit points' are six key road features represented as 'nodes'.

The proposed ABM has been built in NetLogo software. The unit of modelling in the transportation model is individual vehicles (as agents). Vehicle agent's movement on the road network and their interaction with transport infrastructure (including other vehicles) requires a suitable feature to represent the modelled area. The canvas, where the geographical position of agents is placed, is referred to as 'NetLogo World' in the NetLogo software. Patch is a square cell unit similar to a cell in a chessboard. The modelled world is divided into patches of equal size. The nodes as listed above are represented in one patch. The user of the model needs to load the coordinates of these nodes organised as input coordinates file as described in Section 5.3. An intermediate point in a road (i.e. road segment) is represented as a patch and Table 5.1 presents key patch variables. The following sections discuss the implementation of each transport element in the NetLogo model.

Table 5.1 Key properties of a road segment in the ABM

Variable name	Description
Xcor, Ycor	Coordinates of the patch
Road?	Is the patch a road?
Road speed limit	in Km/hr
Junc-id	ID of the next junction
Junc-xcor, Junc-ycor	Coordinates of the next junction
to-junc-dir	Heading/direction to the next junction

A junction is a point along the road where more than two road segments meet/leave. Each road junction is a patch in Orange colour and has an ID with format 'J#' (e.g. J16). The patches around the junction are grey in colour indicating a lower speed limit. As a vehicle approaches a junction (grey patches), it reduces the current speed. This is needed to change its heading at the junction towards next outward junction (as per route plan) and enable safe exit in sharp turns. Table 5.2 is a list of key variables in a junction.

Table 5.2 Key properties of a junction in the ABM

Variable name	Description
Xcor, Ycor	Coordinates of the patch
Junction?	Is this patch a junction?
Junc-id	ID of the current junction (Format J# e.g. J21)
Junc-xcor, Junc-ycor	Coordinates of this junction
to-junction	Ordered arraylist of outward junction IDs from this junction
to-junc-dir	Ordered arraylist of Heading/direction to the next junction

How is the road network created in the ABM? A junction property coordinate file contains organised information about each junction. From the junction property file, the details such as 'coordinates, junction id and outward junctions (to-junction)' are loaded for each junction as patch properties. First the 'Junction?' flag variable is set as TRUE indicating the patch as junction. During run-time, road segments are dynamically drawn by an inbuilt sub-routine from each junction using a tracer-car. This tracer-car is a vehicle agent that is used in the initial setup to create transport infrastructure from a blank NetLogo World. After completion of setup, the tracer-car is removed and not considered among evacuating vehicles.

For example, the patches between two junctions J1 (x1, y1) and J2 (x2, y2) are to be created as road segments. A tracer-car moves from J1 (x1, y1) junction towards the next outward junction (J2) by moving one patch at one cycle. Each patch along the tracer-car is set with properties such as road speed limit, forth coming junction (to-junction=J2) and heading (to-junc-dir). The colour of centre-line of the lane is indicated as white patches. This step is repeated for each outward junction of every junction.

This completes the creation of 'road network' based on junction data for a modelled city. For preparing the junction coordinates, the users can use any digitising software and identify key junctions from an imported road map. It needs to be observed that only one lane of a one-way road is created in the transportation model. For two lanes, two tracer-car needs simultaneously to move in the procedure listed above. Each direction in a two-way road is treated as one separate road.

Any exit point will have one or more inward road segments and no outward road segment. Exit points have an ID with format 'X#' (e.g. X10). Any origin point will have one or more outward road segments and no inward road segment. Whenever a vehicle reaches its destination, the vehicle will be hidden and will not interact with any other agents in the model. There are other nodes in the road network namely ‘intermediate points, pickup-points and traffic signals’ and are discussed in the sections below.

A road segment may not always be a straight line. A road segment between two junctions is better implemented in NetLogo using square patch units when it is nearly a straight line. This is needed to facilitate manoeuvring of moving vehicle patch by patch. The users while preparing the junction coordinates could identify ‘intermediate points’ indicating where the heading of the road changes and ensure road segment between two junctions is possibly a straight line. If needed, an intermediate point is added as additional node between two junctions. ‘Intermediate points’ have an ID with format ‘I#’ (e.g. I15). Intermediate points are also junctions and have properties as listed in
Table 5.2.

Pickup-points are specific location along the road where ‘evacuation buses’ stop to pickup evacuees waiting for public transport. Pickup-points have an ID with format ‘P #’ (e.g. P13). Pickup-points are also junctions and have junction properties as listed in
Table 5.2. Apart from these variables, details about the waiting evacuees are listed as properties. This architecture is similar to DYNEV evacuation model (Qiao et al. 2009), where the evacuation bus route information is to be inputted as ‘route, schedule, and stopping locations’. Table 5.3 summarises key variables of a Pickup-point.

Table 5.3 Key properties of a Pickup-point in the ABM

Variable name	Description
Junction?	Is this patch a junction?
Junc-ID	ID of a pickup point (e.g. P13)
Pickup-Pt-Flag?	Is this patch a bus pickup point
Pickup-ID	ID of a pickup point (e.g. P13)
Waiting-evacuees	Are there any evacuees waiting for bus?
Queue-ID	Sequence number of evacuees waiting in queue
Queue-House-ID	Arraylist of IDs of the house agent who are in queue
Queue-Family-Size	Arraylist of size of family waiting in queue
Queue-Arrival-time	Arraylist of household’s arrival time at the queue

A traffic signal is another object in the evacuation road network. Traffic signals have an ID with format ‘T#’ (e.g. T13). Traffic signal coordinate file contains properties about each signal station. Key properties are location coordinates, signal ID, approaching junction ID and signal sequence number. A traffic signal is typically located on each approaching road towards a road junction for safe movement of vehicles. Generally, signals of each junction are synchronised to sequentially change colour in an orderly manner. Each signal will have a sequence number (1, 2 … n) to indicate the order in which the signal will change its colour. A tracer-car creates these signal stations and sets the properties of signals during initialisation stage. The duration of green colour is specified in the phase-length variable. Table 5.4 presents key variables of signal object.

A signal station rests on a particular location coordinate (Xcor, Ycor). The patch below a signal station is yellow in colour and set with specific properties as listed in Table 5.4. About five or six patches on the road segment preceding a signal station is treated as 'signal visibility zone'. Any vehicle entering this zone will be impacted by the colour of signal and respond to it accordingly. The patches in signal visibility zone are set with properties of the signal associated to it.

Figure 5.5 is a screenshot of a typical junction in the ABM. In Junction J16, there are two approach roads from P15 and J14 (indicated by black arrows) towards the junction and one outward road towards J15. There are two signals namely T12 and T13. Red car agents are evacuating vehicles stopped ahead of a red signal.

Table 5.4 Key properties of a signal station in the ABM

Variable name	Description
Breed?	Signal
Xcor, Ycor	Coordinates where the Signal station is located.
Colour	Current Signal colour (Red/Green)
Time-to-change	How many units to change the current colour?
Phase-Length	What is the duration of Green?
Signal-Junc-Id	What is the ID of the approaching junction?
Who	Agent-ID for the signal object
Signal-Junc-Order	The sequence number indicating the order of this signal among the signals in the same junction.

Table 5.5 Key properties of a patch below a signal station in the ABM

Variable name	Description
Signal?	Whether the current patch is a signal?
Signal-ID	Agent-ID of the Signal posted in the current patch
Signal-Code	A unique ID for the signal (Format is T#. e.g. T42)

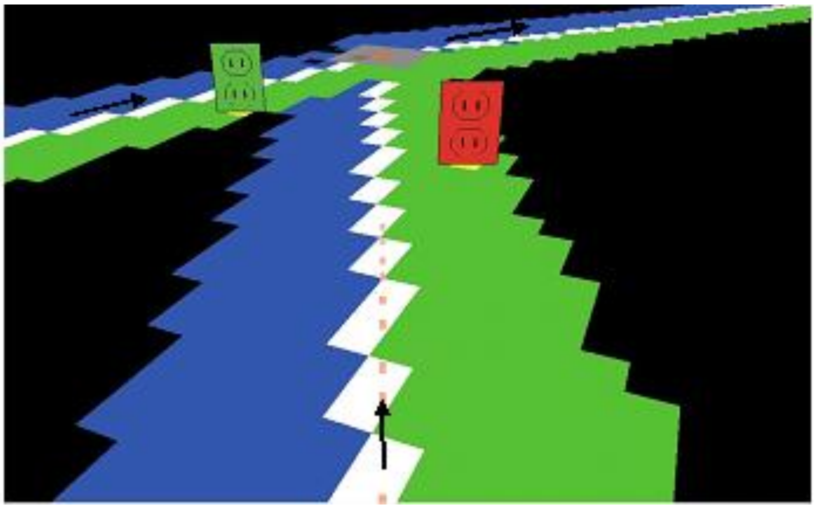


Figure 5.5 Screenshot of a typical junction (J16)

5.4 ABM Transportation model - loading ERGO city's evacuation details

5.4.1 Overall architecture of the model

The proposed multi-modal ABM in NetLogo can be configured to represent the road network of any city and illustrated using the ERGO city case study. The NetLogo programming language allows further customization to have context-specific features that were not included in the model (e.g. roundabouts). The approach adopted in building this customisable model enables the representation of transport features as points. In order to configure the ABM, all the transport infrastructures (road junctions, intermediate points, pickup-points, exit points and traffic signals) need to be organised as 'point data', formatted with suitable names and with relevant information pertaining to each feature. Detailed information on the sequence of variables for each file has been presented in Appendix A. Table 5.6 is the list of coordinate files. At the setup stage of the model, the users can load the evacuation routes after removing road closures and any unavailable routes.

During an earthquake in Southwest China (September 2012) about 700,000 got impacted and 100,000 had to be evacuated as there were damages to 20,000 houses. During the evacuation, an official from Luozehe Township claimed that "*The hardest part of the rescue now is traffic. Roads are blocked and rescuers have to climb the mountains to reach hard-hit villages*" (Rediffmail 2012). The damages to the road network can impact not only the search and rescue efforts, but also the evacuating population. This entails a need for understanding the vulnerability of road network to planning scenario and its impact on evacuation.

Table 5.6 List of Model coordinate files for configuring Modelled area.

File	Brief description
"ERGO-City-Image.jpg"	Image of the modelled area.
"evacuation-zone-coordinates-file.prn"	Coordinates of each zone and bus pickup-points
"household-warning-time-file.prn"	Household information such as X, Y coordinates of household, warning time, departure time, means of transport, zone, etc
"road-network-connectivity-file.prn"	Coordinates of road junction points, heading and outward junctions from this junction.
"traffic-signal-details-file.prn"	Location of traffic signals
"evacuation-route-to-exits.prn"	O-D route plan from each zone (loading point) to exit-points.
"evacuation-route-to-shelters.prn"	O-D route plan from each zone (loading point) to Shelters
"evacuation-route-loading-points.prn"	Loading point for each zone
“bus-route-file.prn”	Route plan for each evacuation bus route.
“transient-vehicle-routes-file.prn”	Route plan for each transient vehicle route.
“shelter-coordinates-file.prn”	Location of each shelters

These coordinate files can be sequentially loaded into the NetLogo model in the setup stage as information/data layers. This architecture of the model allows customisability of the model to other cities by organising data in pre-formatted coordinate files. A temporary car (tracer-car) dynamically reads the coordinate file and creates (draws in the model canvas – NetLogo World) road features along with its properties. This setup module has been written in NetLogo to load the modelled area information.

Users of the model will input at the setup stage ‘percentage of resident population who will not comply with the evacuation order’. Additionally, the user will input the proportion of evacuees who need public shelters and others will be considered leaving outside the city to friends, families or private accommodation. The latter type of evacuees are assigned the nearest exist point as their destination. The shortest route from the origin (evacuated zone) to the destination (both shelters and exit points) is inputted along within the coordinate file. The summary of input data provided to the model and key output metric is presented in Table5.7. Once the setup is complete the model is initialised with setup values and ready for execution. The next section elaborates on the setup stage configuration of model area and calibration.

Table 5.7 Input and output parameters of the transport model.

Parameter	Type of Parameter	Description
Road network	Input file	Coordinate file-1 as nodes (junctions and traffic loading) and arcs (roads)
Evacuation route	Input file	Specify the directions and lanes as a property for roads in the coordinate file -1
Evacuation zone details	Input file	Coordinate file-2 details of the zones to be evacuated, vehicle ownership, number of residents and warning received time
Means of Transport (%)	Input [Evacuee Behaviour]	Select the percentage of car users, pedestrians and public transport (bus) users on screen
Evacuate-or-Not (%)	Input [Evacuee Behaviour]	Select the proportion of evacuees who will not evacuate.
Evacuee destination (%)	Input [Evacuee Behaviour]	Choices for each zone are specified in evacuation-routes to exits/destination file.
Desired Safe speed	Input [Driving behaviour]	Select on screen whether 'desired safe speed' is modelled as uncertain or deterministic.
Perceived safe gap	Input [Driving behaviour]	Select on screen whether 'perceived safe gap' is modelled as uncertain or deterministic.
Time of the day	Input [Scenario]	Defines the initial location of the vehicles prior to evacuation. User will select either it is night-time or daytime.
Transient traffic condition (vehicle/hour)	Input [Transport policy]	User can select the volume of transient traffic in expressways in the screen.
Evacuation Bus	Input [Transport policy]	User can select yes/no for including 'Evacuation bus' in the screen.
Evacuation time (min)	Output	Time between the departure from the household and reaching the chosen destination.
State of evacuation	Output (Graph)	% Evacuees who are i) on transit to destination, ii) reached destination iii) not evacuated/ in-situ

5.4.2 Configuration of model environment to ERGO city

The contribution of this thesis is to integrate the household transport behaviour choices, performance of warning dissemination and subsequent evacuation (as vehicle agents) to safety (shelters). This enables the study of inter-relationships among the ESFs for the modelled area. The model area's boundaries are identified and the rectangular coordinates are specified as NetLogo world corners. The modelled area is divided into square units called patches. By iterations on the accuracy of road network traced, the unit size of patch has been iteratively determined. One patch length = 16.67 m (1000/60 m). The overall modelled area is 39.3 km x 50.7 km.

Calibration of ERGO city to NetLogo World

Apart from the patch, another basic unit is time referred as ‘time slice’ or a tick. Shorter the tick, the more will be the number of iterations and the longer will be processing time. However, when one tick is too large, there will be loss of accuracy in the model as a large tick will result in longer distance to move in the next time step when a car is at its peak speed and hence might miss a junction point.. Such errors can lead to cars missing a junction where it needs to change its heading and might stop on the sides of road. Unit tick is computed iteratively by checking tracer-car traversing through the road network and was found that 1 tick = 0.02 minutes is a suitable value. The unit tick value used in this thesis is slightly higher than the ‘time slice’ (1 second) of existing traffic simulators (Schulze and Fliess 1997, p1224), which is the mean reaction time of drivers. Any value below this will increase the processing time. And any value above this will result in inaccuracy. Once these basic units (patch and ticks) have been calibrated for the modelled area (ERGO city), the other dependent units and conversions were computed and are given in Table 5.8. Key driving behaviour values namely speed and safe gap are presented in Table 5.9.

Table 5.8 Calibration of model values to actual values of ERGO City

Variable	Value	Brief description
Basic Units		
1 patch length =	16.67	Meters or (60 patches = 1km)
1 tick =	0.02	minutes
Conversion Multipliers		
one-patch-to-km	0.017	Converting 1 patch into km
one-patch-to-m	16.67	converting 1 patch into m
tick-to-minute	0.02	Converting 1 tick to minute
tick-to-hour	0.00033	Converting 1 tick to hour
distance-km-to-patch	60	Converting 1 km to patches
distance-patch-to-km	0.0167	Converting 1 patch to km
minutes-to-ticks	50	Converting 1 minute into ticks
hours-to-ticks	3000	Converting 1 hour into ticks
speed-kph-to-patchpertick	0.02	distance-km-to-patch / hour-to-ticks
accl-mpsec2-to-patchptick2	0.0864	(distance-km-to-patch / 1000) / ((minutes-to-ticks / 60) * (minutes-to-ticks / 60))
accl-mpsec2-to-kph2	12960	(1/1000)*(3600* 3600)

Table 5.9 Key driving behaviour parameters and values

Variable	Values
Vehicle driving speed behaviour	
Vehicle Speed limit (km/h)	70
Desired speed average (km/h)	40
Desired speed std-dev (km/h)	10
Minimum desired speed (km/h)	30
Car acceleration rate (m/sec^2)	2
Car deceleration rate (m/ sec^2)	2
Vehicle safe gap uncertainty	
Average (m)	15
Std dev (m)	5
Minimum (m)	10.1
Maximum (m)	20

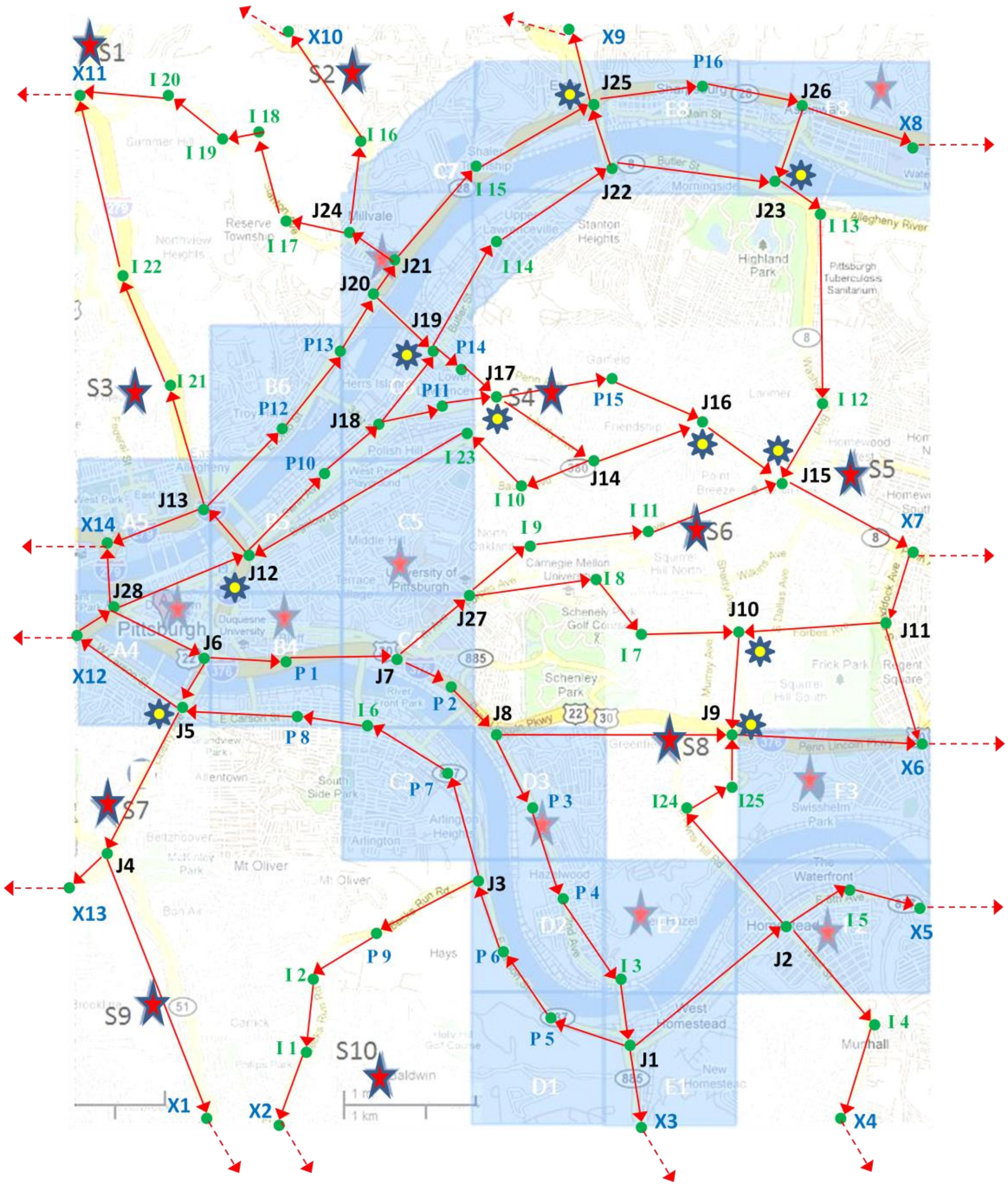
ERGO City case study - Transport network details

The flood inundated regions of ERGO city need to be evacuated as indicated by Figure 5.6. The model will include three expressways and all the major roads in the ERGO city. Alleys and streets will not be within the scope of the work, as the evacuation from the household to the traffic loading point is assumed to be uniform within an evacuation zone. Arrows indicate the direction of roads between two junctions. Dotted arrows at exit points indicate traffic moving outside evacuation zones and considered to be beyond the boundary of the modelled area.

Table 5.10 presents the overview of ERGO city evacuation characteristics, evacuation network and volume of traffic. It can be observed from the table that only 9214 houses are in the inundated zones (indicated as blue in Figure 5.6) and need to be evacuated. However, depending on the level of warning, warning scenario and level of compliance with warning, the actual number of evacuated houses will be lower.

Table 5.10 Overview of ERGO city evacuation characteristics and values used

Model characteristics	Value
i) Demographic details	
Number of houses	31617
Resident population of the modelled area	129021
Number of zones to be evacuated	19
Number of houses in the evacuated zone	9214
Resident population to be evacuated	37619
Number of shelter locations	10
ii) Road network details	
Number of major roads	4
Number of road intersections/junctions	28
Number of traffic signals	10
iii) Evacuation traffic	
Number of evacuating cars	One per household
Number of evacuation buses	One per route
Number of bus routes	4
Bus is dispatched after onset of warning	30 minutes
Frequency of bus	Every 10 minutes
Number of destinations (or exit points)	14
Number of 'destination choices' per evacuation zone	3 to 7 (average 4.7)
Number of 'shelter choices' per evacuation zone	1 to 6 (average 3.7)
Number of evacuation bus pickup points	16
Number of evacuation bus routes	4
Number of transient vehicle routes	4



Legend:

X1… X14 →Exit points

P1… P16 →Pickup points for evacuation bus.

J1 … J28 →Junctions

I 1 … I 25 →Intermediate locations along roads.

→ Traffic signal

→ Shelters

Figure 5.6 Evacuation road network of ERGO city

Transient traffic is due to commuters who travel via the ERGO city, delivery trucks and other road users. There are four transient routes in the ERGO city and has been presented in Figure 5.7. For a single-lane roads, the vehicle flow rate at peak hours typically is in the range between 500 vehicles per hour and 2000 vehicles per hour (Wolshon 2006, p4). When this transient traffic in the expressway is diverted from the evacuation routes in order to have more capacity available for evacuation, it could possibly reduce the overall ET and requires further investigation using the model.

In this study, there are three classes of transient vehicle conditions as a 'transport policy' which the user can select on the screen. They are 0 – No transient vehicle, 1 – Low volume (300 vehicle/hour vph) 2 – High volume (600 vph). User can select this data on the input screen depending on the scenario to be tested using ABM. The selected flow rate will be applied to all the transient routes. In run-time, new transient vehicles will be loaded on each route at the specified flow rate, and the vehicles will traverse along the transient route plan. Once the vehicle reaches their exit points, these vehicles will be treated to be beyond the scope of the model.

There are four bus routes as indicated in Figure 5.8. Buses stop at pickup points along the route until it reaches the destination. The return leg was not modelled in this thesis. Each bus carries evacuees to public shelters and assumed that no evacuees will off-board en-route. Bus route 1 has final destination in J9 and serves shelters S5, S6 and S8. Bus route 2 has final destination in J15 and serves shelters S4, S5 and S6. Bus route 3 has final destination in X10 and serves the shelter S10. Bus route 4 has final destination in J15 and serves shelters S7 and S9. The following are the model assumptions and simplifications.

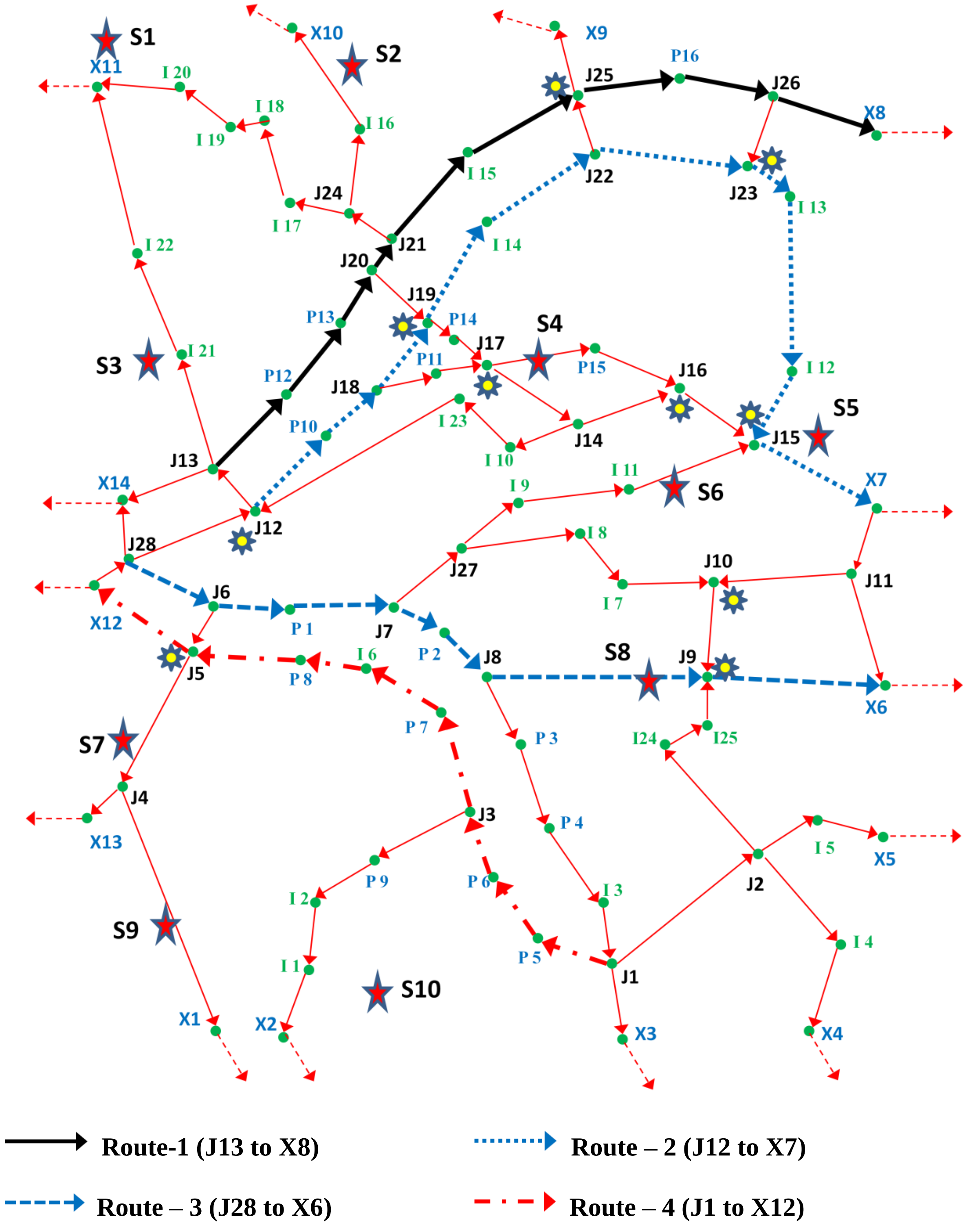


Figure 5.7 Four transient routes within the evacuation network.

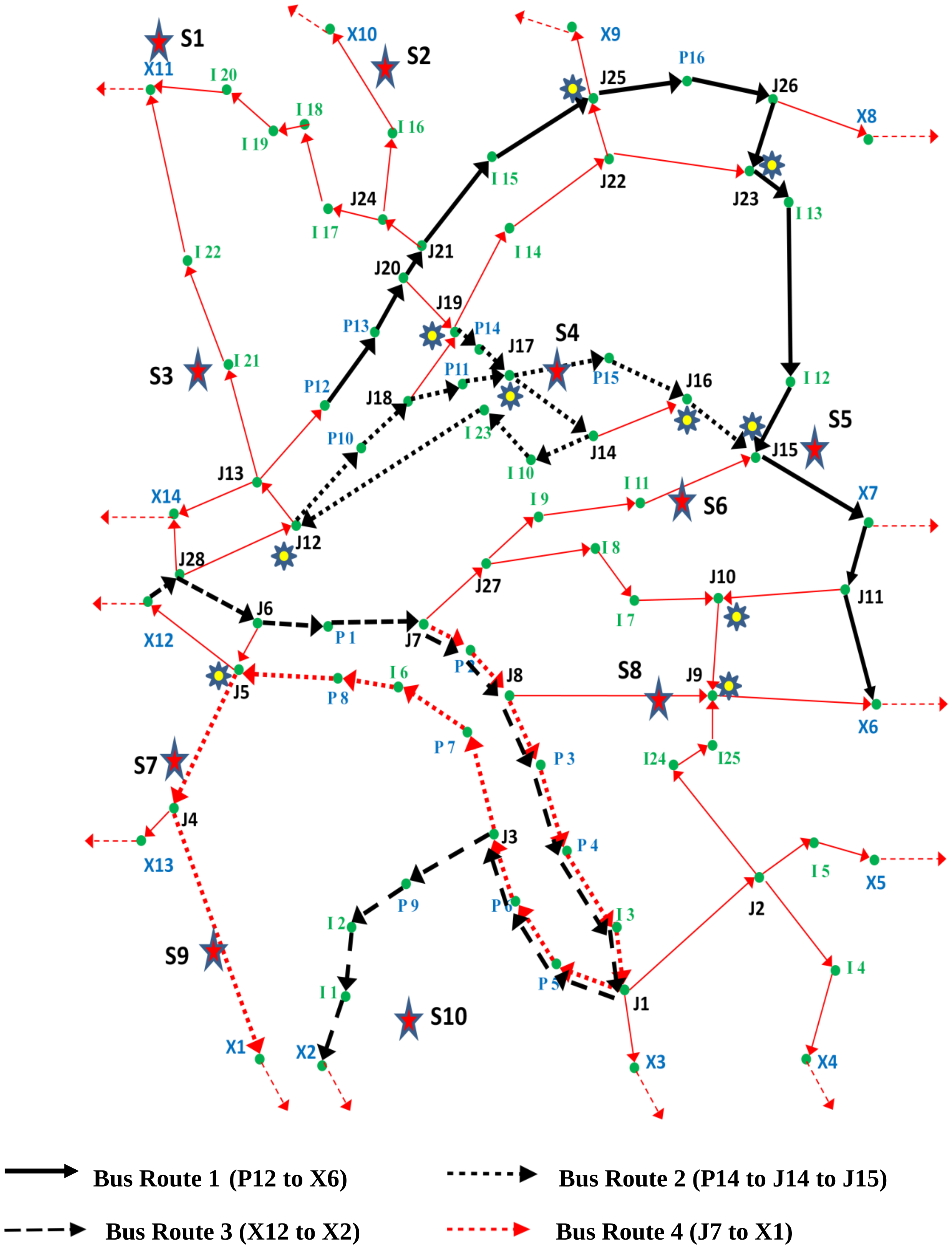


Figure 5.8 Four evacuation bus routes.

Model assumption and simplification

1) Alleys and streets were excluded as simplification of road network.
2) Evacuation using bus, pedestrians and car has been considered in this model. Other means of transport has not been included which can provide additional capacity to the evacuating traffic.
3) When the model begins execution, the condition of traffic is to have only transient vehicles.
4) Night-time evacuation is considered in the model and hence evacuation begins from the household to destination. During day time, some of the family members will be in places other than residence (e.g. office, school, etc) or on transit. This scenario has not been considered in this thesis and can be taken up in further research.
5) Pedestrian movement has no influence on the road traffic movement (car, bus or transient vehicle).
6) The houses evacuating as pedestrians have destination as shelters.

Figure 5.9 is a screen shot of the transport model. At the input stage, EMAs need to import this information for their city into the transport model. There are transport policies in the evacuation plan and the details of the evacuee behaviour which the users can select on screen at the setup stage. The user will select the planned estimate of different modes of transport and the estimate of number of evacuees who will require sheltering.

Once the user has completed the setup stage, the simulation model can be run to obtain aggregated results. This multi-model agent-based traffic network model will provide a platform for the transport authorities to understand the interplay of the existing road network configuration, public transport usage and the evacuee behaviour by their choice of mode as well as destination. The following sub-section elaborates on the implications of diverse transport management options available for the authorities to plan for evacuation traffic management. Understanding these response choices and their relative performance in ensuring a safe evacuation will be an important consideration for the evacuation transport preparedness. In summary, the approach taken in the ABM model will be customisable to any city and illustrated using the ERGO city.

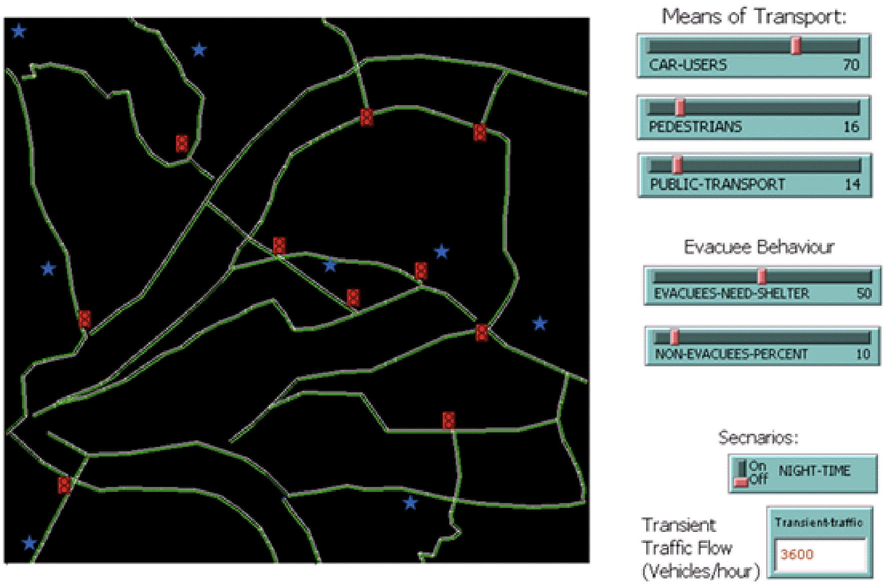


Figure 5.9 Screenshot of the evacuee transport model

5.4.3 KPI for measuring evacuee transportation

The ET is defined as the time for each household from leaving the house after receiving warning message to the time when they reach the destination. Clearance time is defined as the "*time required to get evacuees out of hazardous areas to a place of safety*" (Chen et al. 2012, p207). The ET is chosen as the key performance metric for measuring the effectiveness of a transport plan. This has been used as output metric in the published literature as well. An example policy question from Chen et al. (2006, p.325) is, "*What is the minimum clearance time needed to completely evacuate 92595 persons (residents plus transient tourist population)*?

"*The evacuation clearance time is one of the key indicators in an evacuation plan and is determined by the expected behaviour of the endangered residents and roadway network characteristics*"(Tu et al. 2010). Based on the review of literature on KPIs for evacuation transport management, this thesis has been summarized in Table 5.11 basic KPIs for monitoring evacuation traffic performance into three broad categories.

These KPIs will be collected after each simulated run. Implementing transport policies like alternative routing strategies, signalling, capacity enhancers (like contra-flow plans), etc can increase the network capacity of the transport infrastructure. It can be noticed that for evacuation transport planners, the interest lies in the first set of KPIs. However, there is a close link between the existing network capability (KPI-2) and public transport resource allocation (KPI-3). Many organizations are involved in the overarching transport management such as 'transport operators' (bus owners) and transport regulators (managing traffic including signalling and policing). This entails a need for co-ordination and a purposeful collaborative working among these organizations for evacuation preparedness and subsequent response. Household choices influence the direction of traffic and hence understanding the interplay of household behaviour and transport policies.

Table 5.11 KPI measures for transportation model

KPI group	**Measures**
Evacuation performance	Overall evacuation time, clearance time, departure time and evacuation speed.
Network capability	Hourly flow rate, flow density, busiest junction and busiest road segment
Resource allocation	Evacuation bus usage on different routes, bus utilization on various trips, number of trips to complete evacuation.

Depending on the household choice of shelters, public shelters could serve as a concentration point for traffic flow with evacuating vehicles moving towards them. *What % of households need shelters? Will a household use car(s) or wait for public transport?* These are typical questions of interest not only to shelter operators but also to transport planners. In general, these shelters are identified and operated by local authorities. The impact of transport management has a direct bearing on the safety of evacuating public including their timely reaching to safety/public shelters. The focus of evacuation preparedness should not be restricted within the ESF organizations' preparedness rather on a collective and coordinated preparedness. This thesis advocates the need for an integrated approach for evacuation preparedness beyond an ESF with special emphasis on the role of OR-based models as a means for strengthening preparedness.

5.4.4 Simulation experiment design

For the same initial setup of agents' parameters (e.g. means of transport), there could be variation of KPIs between runs due to randomness in the agent parameters (e.g. desired speed) during model execution and agent behaviours (e.g. destination choice and evacuation route plan). For example, a household's 'means of transport' remains the same across runs, but the destination and evacuation route plan are agent's decisions at the time of departure. This could influence the travel time and evacuation time to safety.

In order to design simulation experiments, the following are key questions to be answered:

- What is the impact of initial state and transient phase on the model results?
- How many runs are needed to obtain unbiased KPIs?
- What is the run-time of the model (or) how long should a model be executed in a single run?

An introduction of the concepts on validity and reliability of simulation model results used in this thesis was presented in the warning dissemination model (Section 4.6). Similar to the ABM warning model, the transportation model was studied for validity and reliability.

Initial state and transient phase of the model

As discussed in the Section 5.4.1, the details of evacuating households are set using the various coordinate files. The following (set – 1) are the properties of a household and evacuation system that will remain constant across simulation runs.

- A household's mobilisation time (time required for the house to prepare for evacuation after being warned)
- Which means of transport to use for evacuation? {Car, Bus, Pedestrian}
- Whether the household will use public shelter or private accommodation (exit point)?
- Evacuation road network (road network length, direction, loading points, speed limit, signal location and signal phase length)
- Evacuation bus system (bus route, pickup points, capacity, first dispatching time and frequency).

The following (set - 2) are the evacuation decisions and agent properties that will be set in run-time and will change across simulation runs.

- A household's warning time (either with or without unofficial channel)
- A vehicle's driving behaviour (desired speed and perceived safe gap)
- Route to destination (evacuation route plan based on the chosen exit point).
- Route to shelters (evacuation route plan based on the chosen shelter).
- Transport policies.

The first set of household characteristics is considered to be independent of the model scenario and hence set as initial state of the model. The second set of properties are set depending on the scenario of the model and will not be exactly the same for a household between two runs. In order to study the impact of various factors using simulation model, one parameter is changed at a time in a controlled experiment and incrementally quantify the impact in comparison with a base case.

Household evacuation decisions are made prior to departure. For example, {Which exit- point to select as private destination?, Which shelter to select as a destination?} These initial evacuation decisions of an agent will have an influence on evacuation traffic namely which loading point the car will enter based on evacuation plan to destination. In the model, about 15% were assumed to seek public shelter during evacuation.

Table 5.12 Number of zone-wise choices available for a household

Zone	Destination	Shelter
A4	7	6
A5	6	5
B4	6	4
B5	5	4
B6	4	3
C3	5	4
C4	5	4
C5	4	4
C6	4	4
C7	5	5
D1	4	4
D2	5	4
D3	5	4
E1	5	4
E2	4	4
E8	4	3
F2	5	1
F3	4	1
F8	3	3

For households choosing ‘public shelters’ as their destination, column-2 of

Table 5.12 indicates the number of shelter choices available for each zone. For households choosing ‘private accommodation’ as their destination, an exit point (column-1) is selected by a house as its destination. This will influence the volume of traffic moving towards that particular exit point and also on roads leading to it. This zone-wise data has been used while executing the transportation model. The average number of destination choices available for each zone was about 4.74, and correspondingly the average for shelters was 3.74. As households choices are generally influenced by convenience of access to the facility, the individual choices were identified for each zone using its proximity to the zone. These average choices indicate the number of options available for a household to choose from in each run.

Number of runs and run-time of the model

It is important to study the variation between runs due to initial setup conditions and the state changes as the model executes. Similar to the warning dissemination model, it is assumed that ten runs are enough to capture the variation in the model output due to uncertainty in model parameters. The ABM was executed for 10 runs under the same initial setup conditions [such as warning time, means of transport (%), mobilisation time, agent behaviour parameters, etc]. The same configuration files of household properties, warning time and departure time were used across various trials and 'model control variables' are shown in the first column of Table 5.13. KPIs of the evacuated zones were collected for 10 runs and presented in Table 5.13. For one run in the transportation model, a typical processing time (model execution time) in the laptop was found to be 4 hours and 36 hours for runs with scenarios of 'no transient vehicles' and 'high volume of transient vehicle' respectively. The model was executed till the last evacuating household reaches safety (i.e. completion of evacuation).

Summary descriptive statistics such as mean, standard deviation and standard error (Equation 4.1) were measured for 10 experimental trials. Table 5.14 summarises the variation of evacuation KPIs between runs.

The results showed that:

- The average clearance time was the highest for houses using evacuation bus (131.16 minutes) followed by pedestrians (106.69 minutes) and the least time while using cars (79.14 minutes). The standard error was found to be small (0.16) and varies between 0.16 and 0.41. In comparison to the respective means, the highest standard error expressed as percentage of mean was 0.67% for cars with the overall value of 0.33%.

- The average ET was the highest for houses using evacuation bus (178.38 minutes). The standard error for average ET was found to vary between 0.16 and 0.41. In comparison to the respective means, the highest standard error expressed as percentage of mean was 0.24% for cars with the overall value of 0.16%.
- The average evacuation speed of cars was 24.29 kmph with a standard deviation of 0.14 kmph, standard error of 0.43 and standard error as percentage of mean as 0.18%.
- The average waiting time for households using evacuation bus was 85.82 minutes with standard deviation of 1.34 minutes, standard error of 0.43 and standard error as percentage of mean as 0.49%.

Even though the model was executed only for 10 trials in comparison with Schulze and Fliess (1997)'s thumb rule of 20 runs for unbiased conclusions, the error in the KPIs was low and the highest standard error as percentage of mean was 0.67%. The low error indicates that in spite of variation in household evacuation choices (Table 5.12), the overall KPIs obtained from a single model run are comparable across runs.

Table 5.13 KPIs of transportation model for each experimental trial

		1	2	3	4	5	6	7	8	9	10
Average warning time :	Cars	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39
	Bus	11.42	11.42	11.42	11.42	11.42	11.42	11.42	11.42	11.42	11.42
	Pedestrians	12.92	12.92	12.92	12.92	12.92	12.92	12.92	12.92	12.92	12.92
	Overall average	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31
Average departure time :	Cars	48.20	48.20	48.20	48.20	48.20	48.20	48.20	48.20	48.20	48.20
	Bus	47.22	47.22	47.22	47.22	47.22	47.22	47.22	47.22	47.22	47.22
	Pedestrians	48.90	48.90	48.90	48.90	48.90	48.90	48.90	48.90	48.90	48.90
	Overall average	49.89	49.89	49.89	49.89	49.89	49.89	49.89	49.89	49.89	49.89
KPI: Model runtime (minutes)		348	360	363	357	351	368	364	360	361	360
KPI: Average clearance time											
	Cars	28.21	28.03	29.20	28.21	29.13	27.74	28.71	28.03	27.92	29.38
	Bus	132.09	130.60	133.85	131.47	129.27	130.11	130.17	130.90	132.06	131.03
	Pedestrians	58.93	58.58	57.87	58.20	57.82	57.13	56.78	57.75	57.02	57.81
	Overall	49.14	48.73	49.97	48.93	49.18	48.24	48.88	48.66	48.67	49.63
KPI: Average evacuation time											
	Cars	78.91	78.71	79.91	78.89	79.81	78.40	79.40	78.70	78.61	80.08
	Bus	179.30	177.86	181.07	178.69	176.49	177.34	177.40	178.13	179.28	178.25
	Pedestrians	107.80	107.48	106.77	107.10	106.72	106.03	105.68	106.65	105.92	106.71
	Overall	99.03	98.61	99.86	98.81	99.05	98.10	98.76	98.53	98.54	99.52
KPI: Average 'waiting time' for evacuation bus		87.19	84.74	87.73	86.53	84.28	84.91	84.62	85.45	87.73	85.01
KPI: Average speed of evacuating cars		24.36	24.34	24.23	24.37	24.20	24.32	24.06	24.33	24.58	24.15

Table 5.14 Summary statistics of KPIs from 10 experimental trials

KPI - Output metrics	Mean	Standard deviation	Standard error	Coefficient of variation
Model runtime (minutes)	359.21	5.96	1.88	1.66
Average clearance time (from 'loading point' to 'safety')				
Cars	28.46	0.60	0.19	2.10
Bus	131.16	1.29	0.41	0.99
Pedestrians	57.79	0.68	0.21	1.18
Overall	49.00	0.50	0.16	1.03
Average evacuation time (from 'warning onset time' to 'safety')				
Cars	79.14	0.61	0.19	0.77
Bus	178.38	1.29	0.41	0.72
Pedestrians	106.69	0.67	0.21	0.63
Overall	98.88	0.51	0.16	0.52
Average 'waiting time' for evacuation bus	85.82	1.34	0.43	1.57
Average Speed of evacuating cars	24.29	0.14	0.05	0.59

KPIs for one household (say house-id = 5042) across 10 runs are unlikely to match exactly. However, evacuation planners design transport policies for overall KPIs of all households in evacuating zones. And hence the ET of a particular household is less important as the unit of analysis for KPIs is one or more evacuation zones. Thus based on the low level of error, this thesis argues that the findings on 'overall KPIs' from one simulation run are robust.

As there were no real-life data of actual evacuation results for the ERGO city (being a hypothetical case study), the validity of these results with the actual field observations could not be ascertained and has scope for further research study. The behaviour of household's travel choices, implementation of transport infrastructure using network modelling approach and driving behaviour using car-following model were built using existing established literature. It can be argued that the approach of ABM is rigorous and has a potential to provide robust results to support transportation preparedness. Loss of information due to the low standard error is likely to be small and less impactful in changing a transport policy decision. Hence, the results from one simulation run of ABM are reliable and the ABM is purposeful for overall transport modelling. The following section presents in-depth analyses of model results from one trial and scenario experimental results.

5.5 **Scenarios executed in the model**

The focus of this chapter (ESF-2) is to illustrate model-based estimation of evacuation performance using interactions of household travel choice behaviours, transport policies and resource allocation. First, detailed analyses of one simulation trial results are presented below followed by scenario experiments.

The initial setup characteristics of the model and driving behaviour parameters were given in Table 5.10 and Table 5.9 respectively. The model was executed with 'no transient traffic' and having warning dissemination system of 'siren, PA system and unofficial channels'. Analyses from Section 5.4.6 found that the KPIs from one trial run are robust and hence results from one trial will be used for detailed analyses of evacuation performance. Trial 1 (first column) data from Table 5.13 and Table 5.14 are analysed further and the following are key findings.

- It can be observed in Table 5.13 that from the onset of warning dissemination (time t = 0) the overall evacuation was completed in 348 minutes (run-time).

- The overall average travel time (clearance time) was 49.14 minutes. The lowest average was for the car users 28.21 minutes and the highest was for the bus users (132.09) about 4.68 times more than average clearance time of cars.
- Based on ET, it was found that the 'evacuation using car' was the quickest among other means. The second quickest ET was for 'pedestrian evacuees' of 107.8 minutes about 8.8% more than the overall ET (99.03 minutes) and about 36.6% more than the quickest means (car users). The waiting time for evacuation bus was about 87.19 minutes which resulted in household using bus being the slowest.
- On boarding the bus, on an average the travel time to destination (final bus stop) is within 44.9 minutes. This was computed by excluding waiting time from clearance time (132.09 - 87.19).
- The average car evacuation speed was found to be 24.36 kmph, which is lower than the average desired speed of 40 kmph and road speed limit of 60 kmph (initial setup parameter). This implies that even though drivers desire higher speed, the speed of the leading vehicle, volume of traffic on road (evacuating vehicles and transient vehicles if any) and traffic signals reduced the average evacuation speed.

The response curve is a time-series plot of three components such as percentage of houses 'warned, departed and evacuated to safety'. Figure 5.10 presents the 'evacuation response curves' for three means of transport and overall evacuated zones. Table 5.15 presents the time at which discrete evacuation completion percentages {25, 50, 75, 95, 100} are reached. By looking at Table 5.15 and insets in Figure 5.10, the trend of evacuation levels is broadly an S-shaped curve across transport choices. However, depending on the type of transport, the 'clearance time' and in-turn the 'evacuation speed' varies the gradient/slope of evacuation level curve.

Table 5.15 Comparison of the 'time needed to reach various evacuation levels (%)' for various means of transport

Means of Transport	**Evacuation time in minutes**				
	25%	50%	75%	95%	100%
Cars	60	71	93	132	160
Bus	114	167	239	319	352
Pedestrian	85	102	126	166	225
Overall	65	81	116	216	352

- For all the cases, the slope below 50% evacuation level was higher than the slope above 50% evacuation level and asymptotically approaches between 95% and 100%. When the density of traffic increases (% evacuated > 50%) with more number of vehicles on the network, the clearance time increases and hence ET is longer.
- On average, car users complete their evacuation quickest (in 160 minutes). To complete evacuation, the bus users take 120% (352/160) more and pedestrians take about 40% (225/160) more than car users.
- As evacuation buses carry many households (seating capacity of 60) from various pickup points who simultaneously reach safety/destination, the evacuation curve shows step-wise trends.

As the volume of traffic will affect the ET, one of the busy road segment (P8 to J5) and junction (J5) was selected for monitoring during evacuation time. For every minute, the number of vehicles along the chosen busy road is counted as traffic density. Figure 5.11 presents the time-series data of a busy road.

As a vehicle moves outward from J5, a traffic counter in the junction is incremented by one count. Using the cumulative traffic count, the number of vehicles in 5-minute interval was obtained and the hourly vehicle flow rate (vph) through the junction was calculated as presented in Figure 5.12. This scenario did not have any transient traffic and hence it can give a better understanding of traffic propagation for monitoring.

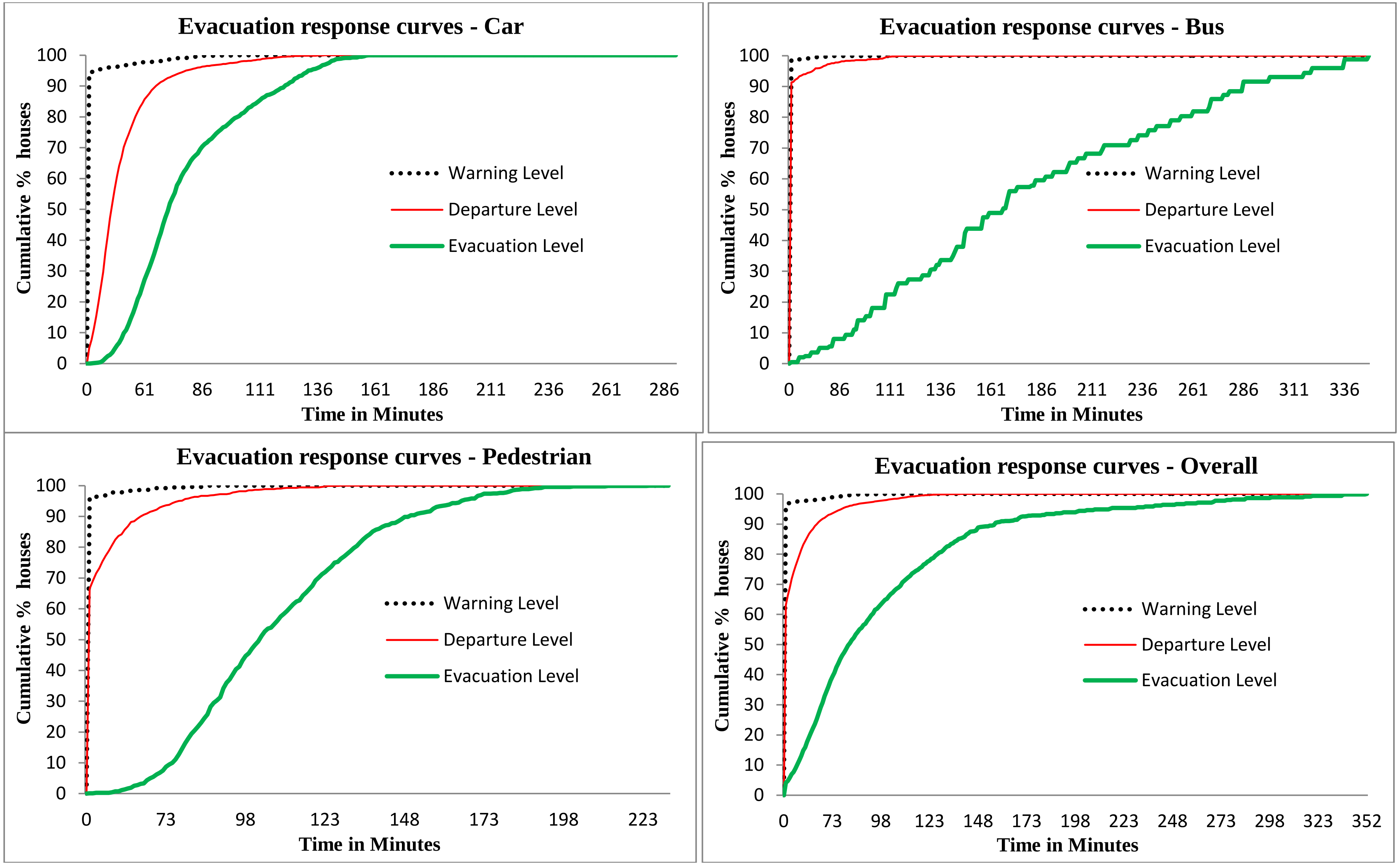


Figure 5.10 Evacuation response curves for different means of transport

From Figure 5.11 it can be observed that the traffic density is low 'before 60 minutes' and 'after 140 minutes'. The density values between 60 and 140 minutes vary between 95 and 120 vehicles in the road segment. By triangulating with the departure curve (Figure 5.10) of cars, it can be observed that this time window is where the major portion of evacuation occurs and the density of traffic is high (Figure 5.11) in the same period.

From Figure 5.12, it can be observed that, the hourly flow rate increases drastically beyond 50 minutes, reaching a peak value of 972 vph at 100 minutes, subsequently decreases gradually to 720 vph in 130 minutes and then drastically reduces. Similar to traffic density, the flow rate is at peak between 50 and 100 minutes.

An evacuating car and the bus will enter into the road network at loading point at their zone. When there are near simultaneous departures, there is a possibility of delay in entering the moving traffic and a virtual queue will be formed based on arrival time in order to enter the network whenever the loading point is free. The model developed in this thesis uses a FIFO principle for allowing queued vehicles to enter road network. By analyses of the model results, Table 5.16 presents the number of houses in various delay categories. The cumulative traffic volume along J1 to J5 was more than 1100 vehicles and the highest 1296 vehicles was for the junction J5. Maximum delays were experienced by households having loading point near J5. The delay to enter loading point will increase the ET of these households.

Table 5.16 Categories of delay time to enter loading point

Delay category	**Number of cars**	**Average delay (minutes)**
No delay	1433	0
< 1 minute	1411	0.15 minutes
Between 1 and 5 minutes	65	2.21 minutes
> 5 minutes	690	27.07 minutes

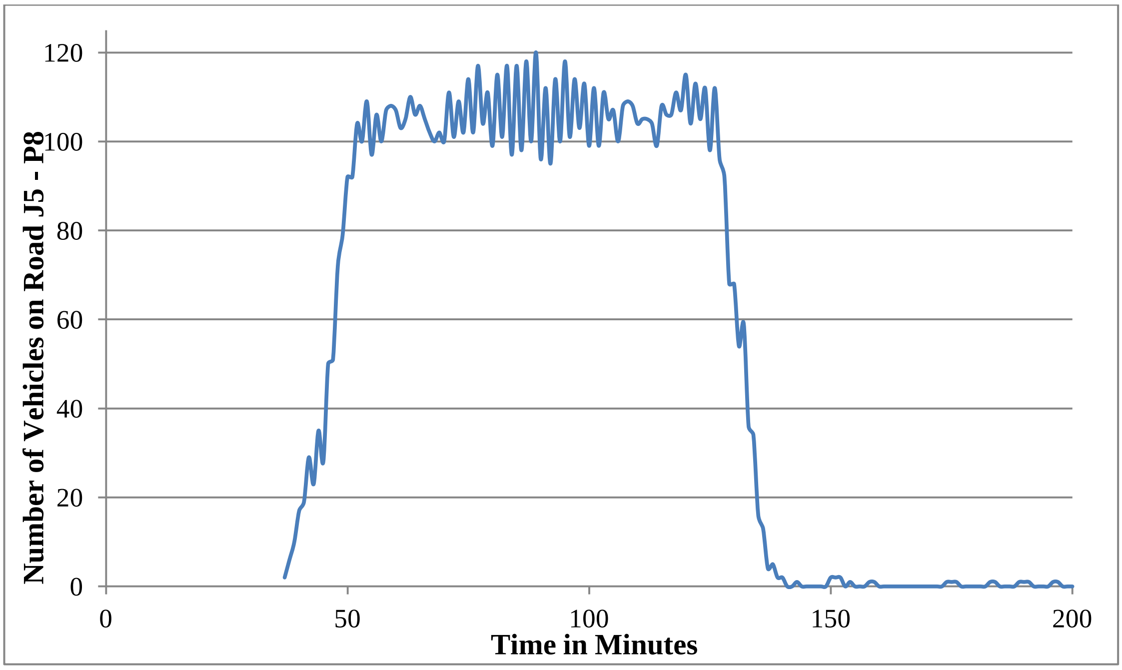


Figure 5.11 Time series of 'traffic density' along a busy road segment J5-P8

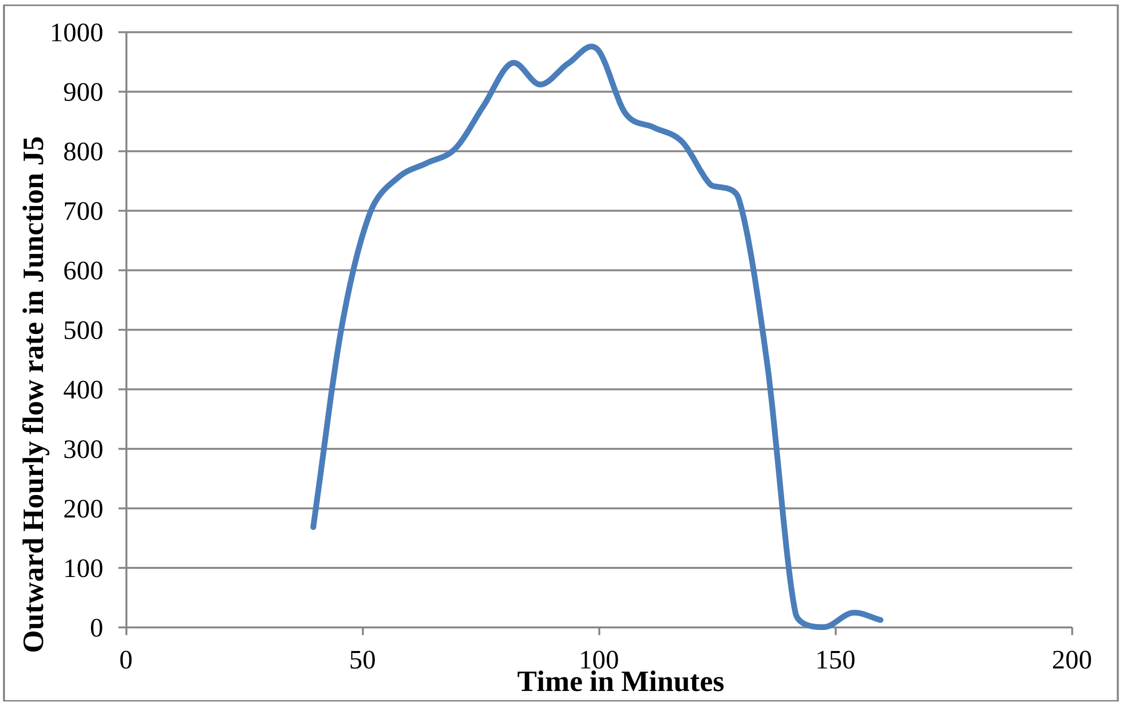


Figure 5.12 Time series of 'outward hourly flow rate' through a busy junction J5

It can be logically argued that the density and flow rate in the peak evacuation window has influence on the delay to enter the loading point, clearance time and hence the overall ET. The experimental trial above was without transient traffic. When the transient traffic is included in the experiment, it will affect the flow rate and density of all roads including the busy roads. It is likely to shift the major evacuation time window and hence delay the evacuation. 'The level of impact on evacuation KPIs due to additional volume of transient traffic' as a scenario is an interesting question for investigation.

It can be logically argued that, during the evacuation window, an increase in road capacity by freeing vehicular traffic will reduce the clearance time. 'Stopping/Diverting transient traffic from using the busy road segment and the junction during this evacuation window' (60 to 140 minutes) could be a traffic management policy. This would prioritise evacuating vehicles to use the road capacity in the busy road.

Clearance time for car users is a function of departure time and traffic volume during evacuation. Departure time is a sum of mobilisation time and 'when the household receives the evacuation message' and hence a function of warning system (ESF-1). It is reminded that warning dissemination is generally managed by other EMAs (police, environmental agencies, etc) and has a direct bearing on ET. This highlights the need for multi-agency based integrated preparedness.

High waiting time for bus made that means of transport as the slowest. *Whether the demand for bus (number of evacuees) was same for all the routes? 'Whether and how' can the waiting time be further reduced for bus users?* These are preparedness questions of interest to transport authorities for further investigation.

To understand evacuation transport dynamics, scenarios were designed and sequentially executed in the model. There are three perspectives of transport dynamics studied as scenarios in the model namely household travel choice behaviours, transport policies and resource allocation.

- The first scenario will study the travel choice behaviour by understanding 'how will the household's warning time and departure time impact the evacuation performance?'
- The second scenario will study an illustrative example for transport policy scenario by answering 'how will controlling transient traffic improve evacuation performance?'

- The third scenario on resource allocation will be studied by understanding ‘How the evacuation bus route can be planned using response curves?’

These three scenarios were taken as key perspectives of evacuation performance and supporting preparedness. There are some more implications of model for the transport planners, and Section 5.6 briefly presents some more scenarios for further research.

5.5.1 Impact of warning dissemination on evacuation performance

The earlier the household receives warning, the sooner will be the departure time and the lower will be the ET. As presented in Section 5.3, departure time is a key household attribute that will influence the loading of evacuating traffic into the road network. The departure time was taken as independent of the ‘means of transport’ and influenced only by warning time and mobilisation time. Mobilisation time is the time taken from receiving message to departing from the house. This time is needed to prepare the items needed during evacuation and depends on ‘household’s evacuation plan’ and preparedness.

The results from two experiments in the transportation model for warning dissemination results (ESF-1) with unofficial (Case A) and without unofficial channel (Case B) are listed in Table 5.17. The houses that only received message from official channel were separately tabulated as second column for case ‘with unofficial’. These results are relevant for direct comparison between two experiments and the following interpretations are by comparing column-2 and 3. The following are the key findings from the experiment:

- Without unofficial warning channel, the number of warned houses reduced by 15% (4376/5142). This highlights that about 15% of the households are un-warned and left behind to be in the danger zone even after the evacuation is complete.
- From a different perspective, the transport authorities when using ‘warning response curves’ without factoring unofficial channel, are likely to underestimate the ‘departure time’ without accounting for ‘time to informing neighbours’.
- Warning-time, a ‘model control variable’, is the same across the two sets.
- As the houses need not inform their neighbours, the departure time (=warning time + mobilisation time) average is lower in case B than case A. By pair-wise comparison of departure time, the difference in values between case A and B was 10.68, 10.6 and 10.93 respectively for car, bus and pedestrian evacuees.

- There was marginal decrease in clearance time by 2.82 minutes and 6.56 minutes in cars and buses respectively from case B to A, due to higher volume of traffic in case A compared to case B.
- Waiting time for bus was 7% more in case A. There are more number of vehicles (houses receiving message from unofficial channel) on evacuation network for case A, and this resulted in more time for buses to reach respective pickup points.
- With delayed departure due to informing neighbours and marginal decrease in clearance time, the ET values were higher in case A compared to case B with difference in values being 11.02, 17.16 and 10.78 respectively for cars, bus and pedestrians. This results in underestimation of ET by 11.95 minutes which is about 12% of overall evacuation time.

In conclusion, having accurate warning response curves (from ESF-1) by including unofficial channel will result in:

a) More number of houses warned and evacuated.
b) Avoiding underestimation of traffic volume of evacuating vehicles and underestimation of ET.

This highlights the need for ‘transport planners’ to work closely with the ‘warning dissemination agencies’ and use more representative warning curves as input to transportation model for preparedness. The sensitivity of mobilisation time and its impact on departure time and further on evacuation performance is another important question for further research.

Table 5.17 Impact of warning dissemination (with/without unofficial channel) on evacuation performance.

	Case A		Case B
	With unofficial		Without unofficial
1. Model control variables	All houses	houses common to both cases	
Number of evacuating houses			
Cars (70%)	3599	3036	3063
Bus (16%)	823	676	700
Pedestrians (14%)	720	594	613
Overall	5142	4306	4376
Average warning time			
Cars	12.39	10.18	10.18
Bus	11.42	9.22	9.22
Pedestrians	12.92	10.48	10.48
Overall average	12.31	10.07	10.07
Average departure time			
Cars	48.20	45.86	35.18
Bus	47.22	44.82	34.22
Pedestrians	48.90	46.41	35.48
Overall average	49.89	45.77	36.82
2. KPI - Output metrics			
Model runtime (minutes)	349		315.06
Average clearance time			
Cars	27.44	30.15	27.33
Bus	129.36	126.73	120.17
Pedestrians	57.46	57.27	57.42
Overall	47.96	49.05	46.05
Average evacuation time			
Cars	78.13	76.01	64.99
Bus	176.58	171.55	154.39
Pedestrians	106.36	103.68	92.90
Overall	97.84	94.77	82.87
Average 'waiting time' for evacuation bus	85.10	81.85	76.33
Average speed of evacuating cars	24.59		23.55

5.5.2 Reducing evacuation time by controlling the transient traffic

The second scenario is to study the impact of transient vehicles on evacuation performance. The base experiment presented in the section was executed without transient vehicles. The expressways in the city are used by vehicles of 'resident population and commuters' and vehicles transiting to some other location. The latter vehicles referred to as 'transient vehicles' will be included in the model in this experiment.

Two categories of transient volume are tested in the ABM transportation model. 'Low-level' category will have flow rate of 4 vehicles per minute (240 vehicles per hour) and 'High-level' category will have eight vehicles per minute (480 vehicles per hour). The category of transient vehicle volume was set in the initial setup stage and the model will dispatch transient vehicles along four transient routes in the specified volume. Similar to the base case, the KPIs of evacuation were collected and tabulated in Table 5.18.

Table 5.18 Impact of transient vehicle volume on evacuation time

	Without transient	**Low-Level**	**High-Level**
1. Model control variables			
Average warning time			
Cars	12.39	12.39	12.39
Bus	11.42	11.42	11.42
Pedestrians	12.92	12.92	12.92
Overall average	12.31	12.31	12.31
Average departure time			
Cars	48.20	48.20	48.20
Bus	47.22	47.22	47.22
Pedestrians	48.90	48.90	48.90
Overall average	49.89	49.89	49.89
2. KPI - Output metrics			
Model runtime (minutes)	359	355	356
Average clearance time			
Cars	28.46	34.70	41.78
Bus	131.16	133.51	137.23
Pedestrians	57.79	60.43	56.97
Overall	49.00	54.12	59.18
Average evacuation time			
Cars	79.14	85.38	92.46
Bus	178.38	180.74	184.46
Pedestrians	106.69	109.33	105.87
Overall	98.88	103.99	109.06
Average 'waiting time' for evacuation bus	85.82	85.94	86.02
Average speed of evacuating cars (kmph)	24.294	22.25	20.85
Average speed of transient vehicles	**N/A**	28.46	27.34

The following are key findings from this scenario analyses:

- The model run-time for completing evacuation was almost the same in all the three cases.
- Overall clearance time from 49 minutes has increased by 10.4 % and 20.7% for cases with low level and high level of transient vehicles. The average clearance time for car users from 28.46 minutes increased by 21.9% and 46.8% respectively for two cases. In case of households using bus, the average clearance time from 131.16 minutes increased by 1.8% and 4.6%.
- The average car evacuation speed from 24.29 kmph, has decreased by 8.4% and 14.2% for the two cases, respectively. These averages are much lower than the average desired speed of 40 kmph and road speed limit of 60 kmph (initial setup parameter).
- In comparison to car's evacuation speed, the speed of transient vehicle within the modelled area was found to be 28.46 kmph and 27.34 kmph. With increase in transient volume traffic, the impact on transient vehicles was marginal and yet the speed was much lower than the average desired speed of 40 kmph and road speed limit of 60 kmph (initial setup parameter).
- Pedestrian clearance time has no impact due to transient vehicles as these agents do not use the road network and do not interact with other vehicle agents as assumed in this thesis. However, the variation in average clearance time for pedestrians was in a narrow range (56.97, 57.79 and 60.43) due to the uncertainty in destination choices in the three runs.

In conclusion, increase in transient vehicle traffic increases the clearance time and delays evacuation. The level of impact on clearance time was considerably higher in the case of cars compared to households using bus. The impact on households using bus was very marginal due to less overlap of bus routes and transient routes. The further reduction in car's evacuation speed by 8.4% and 14.2% is directly due to the transient traffic as all other factors were constants in the three cases. If the transient volume is further increased to a value closer to road capacity, then there is a possibility of increased congestion, resulting in more clearance time and further delayed evacuation.

5.5.3 Evacuation bus dispatching and monitoring plans

Figure 5.2Figure 5.2 presents the flow chart of household decision making for all the means of transport. Relative failure of evacuees dependent on the public transport compared to motorist was highlighted during Hurricane Katrina (Gutierrez 2011). As the ET is the highest for bus users due to high waiting time of about 87 minutes, evacuation bus resource allocation will be of considerable interest to the transport planners.

In this scenario, detailed analyses of evacuation KPIs of bus are made to support resource allocation plans for dispatching evacuation bus. There were four bus routes as shown in Figure 5.8 and evacuees reach the nearest pickup points from their house. Government transport authorities can have resource sharing agreements with the local private bus operators, travel companies, transport services of the neighbouring regions, etc. This will increase the number of evacuation buses available. It is assumed in the model development that 'there is no limitation in the number of buses available for evacuation'. As a simplification, the return leg of the bus is not modelled.

Each row in a 'trip sheet' contains information about the travel information of each bus along a route such as Bus-ID, travel time (departure-time, time of arrival at destination) and capacity utilisation (number of houses transported, number of seats/evacuees filled and vacant seats). An example trip sheet for route 0 is shown in Table 5.20 and trip sheets for remaining three routes are provided in Appendix – B. Such trip sheets help the supervisors at transport operations centre to monitor the bus utilisation across routes. Once a bus reaches the destination, the 'trip sheet' is updated and the bus is removed from the scope of the model.

Some of the transport policy assumptions are as follows:

- All routes will have regular bus dispatched every 10 minutes and the first bus will leave after 30 minutes from the warning onset.
- No zone-wise estimates of bus demand are available and hence it is assumed that all routes are equal in their demand.
- As a planning assumption, 16% of houses needed bus and the households were randomly allocated from evacuation zones.
- Some of the routes are overlapping and hence served by more than one bus.

As the evacuees live in different zones, analyses of model output will be able to provide the level of demand in different routes and the results are presented in Table 5.19. It can be observed from Table 5.20 and Appendix-B that about 15.7%, 6.38%, 35.95% and 41.96% evacuees are from routes 0 to 3 respectively. The demand for buses was highly staggered with major demand from route 3 and route 2.

Table 5.19 Route-wise demand for evacuation bus

Route	Number of evacuees	Number of houses
Route 0	633	128
Route 1	282	52
Route 2	1407	293
Route 3	1680	342
Total	4002	815

The population is not the same in all the zones and hence demand for bus is unequal. Bus routes cover different evacuation zones and evacuees reach the pickup point in their zone. However the bus dispatching scheme was the same (every 10 minutes) across all the routes and could be the reason for high waiting time. In order to understand the trends of waiting time across routes, the bus trips across the four routes need to be reviewed. Trip sheets were generated as a report from the transportation model. The summarised key observations of trip-sheet data are presented in Table 5.21. Figure 5.13 to Figure 5.16 present the evacuee arrival profiles and bus seat utilisation for the four routes.

Table 5.20 Trip-sheet from the model for route 0

Trip-Sheet Sl.No	Bus-ID	Departure-time	Arrival at destination	Clearance time	Evacuees transported	Houses Evacuated	Vacant seats
3	5167	30	65.72	35.72	0	0	60
8	5680	40	80.4	40.4	26	4	34
12	6946	50.16	92.76	42.6	58	13	2
16	7640	60.18	101.78	41.6	60	9	0
18	8175	70.18	104.74	34.56	59	13	1
24	8452	80	123.36	43.36	58	11	2
25	8626	90	123.4	33.4	60	12	0
32	8660	100	141.3	41.3	60	10	0
33	8708	110	141.34	31.34	60	15	0
40	8743	120	153.36	33.36	60	16	0
41	8797	130	159.4	29.4	59	11	1
47	8808	140	172.18	32.18	60	12	0
51	8813	150	184.3	34.3	13	2	47
57	8817	160	196.64	36.64	0	0	60
63	8821	170	208.18	38.18	0	0	60
65	8825	180	217.28	37.28	0	0	60
66	8829	190	220.46	30.46	0	0	60
70	8833	200	224	24	0	0	60
75	8837	210	241.54	31.54	0	0	60
80	8841	220	251.12	31.12	0	0	60
83	8845	230	259.74	29.74	0	0	60
91	8849	240	281.18	41.18	0	0	60
92	8853	250	281.2	31.2	0	0	60
97	8857	260	296.18	36.18	0	0	60
102	8861	270	311.56	41.56	0	0	60
106	8865	280	320.66	40.66	0	0	60
107	8869	290	320.68	30.68	0	0	60
110	8873	300	329.66	29.66	0	0	60
115	8877	310	341.86	31.86	0	0	60

Table 5.21 Route-wise key observations of trip-sheet data

	Route 0	Route 1	Route 2	Route 3
Number of trips needed	13	8	24	29
Number of vacant trips	16	21	5	0
Clearance time				
Minimum	24	19.64	22.7	24.36
Average	35.02	27.47	29.75	36.99
Maximum	43.36	34.44	35.66	59.7

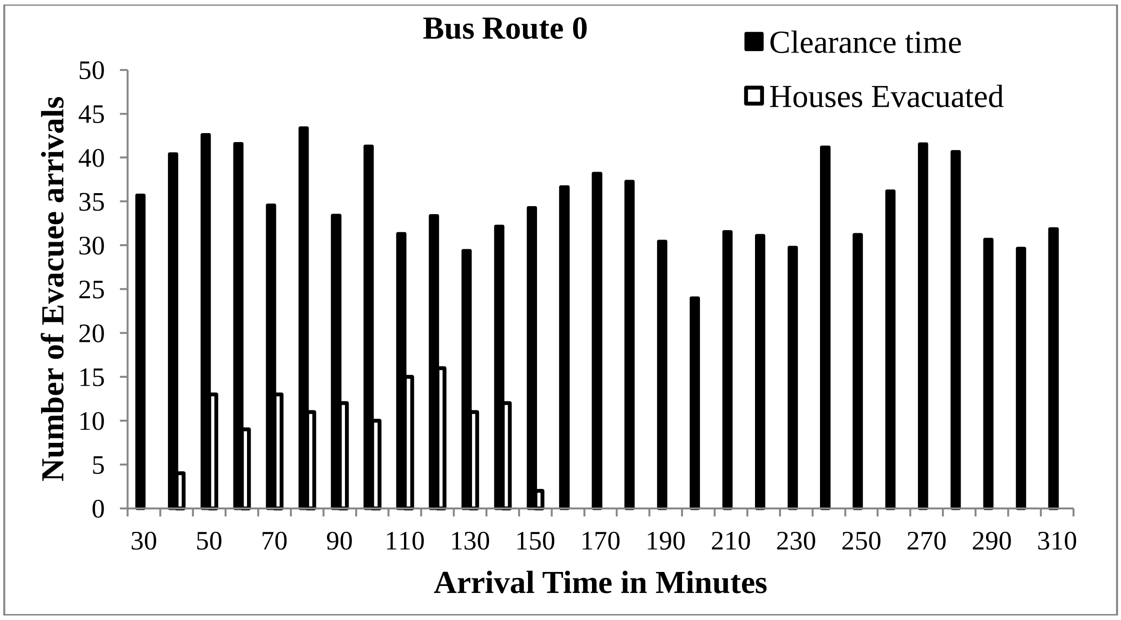


Figure 5.13 Evacuee arrival profiles in shelter and bus capacity utilisation for route 0

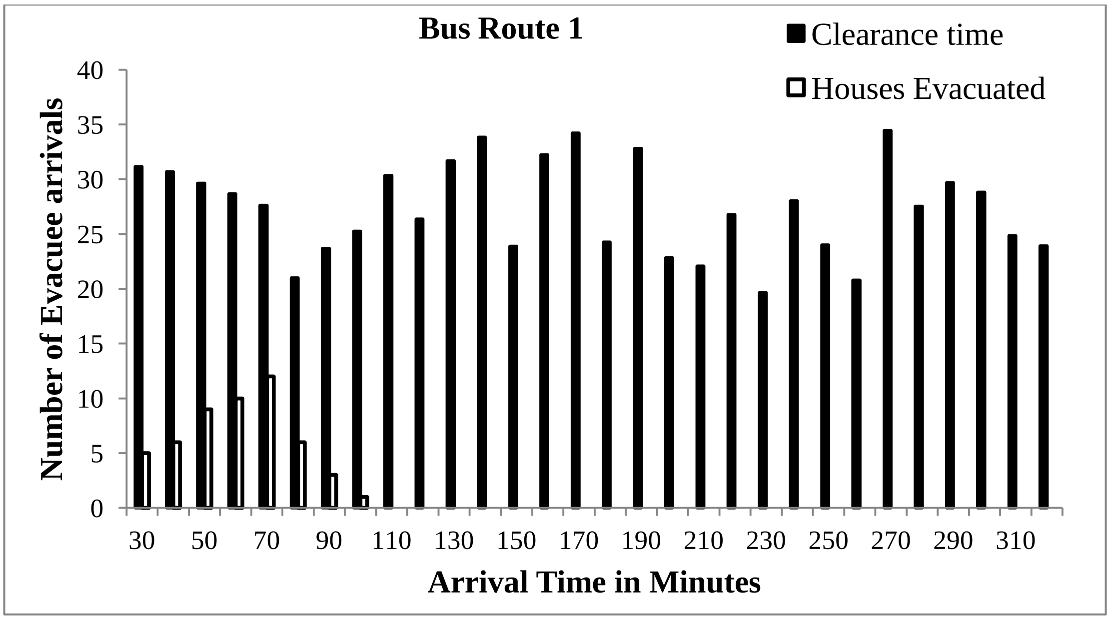


Figure 5.14 Evacuee arrival profiles in shelter and bus capacity utilisation for route 1

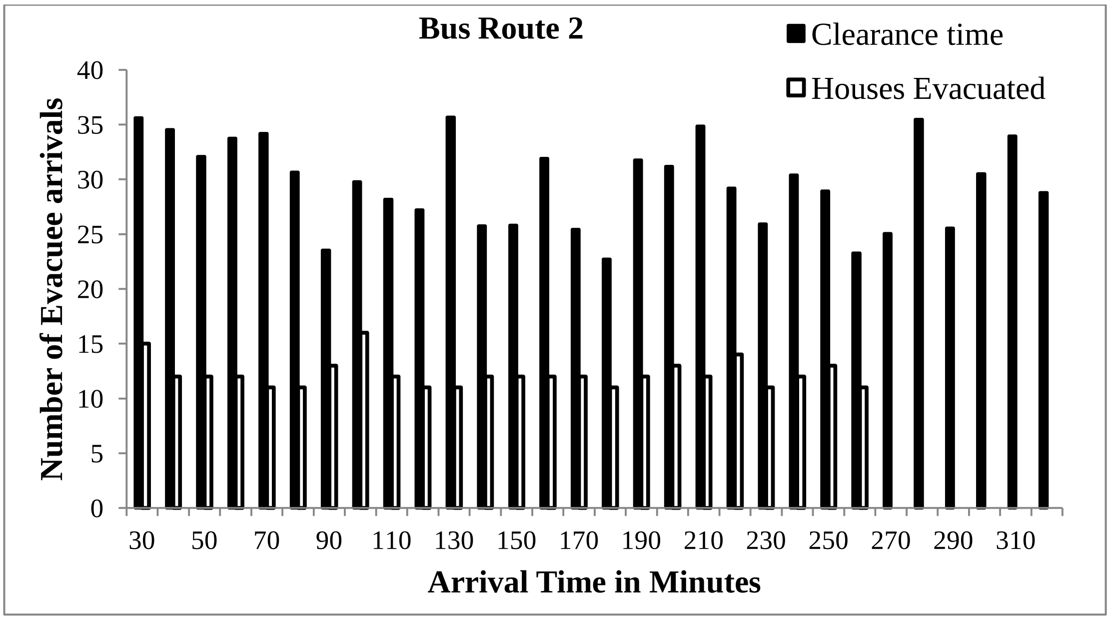


Figure 5.15 Evacuee arrival profiles in shelter and bus capacity utilisation for route 2

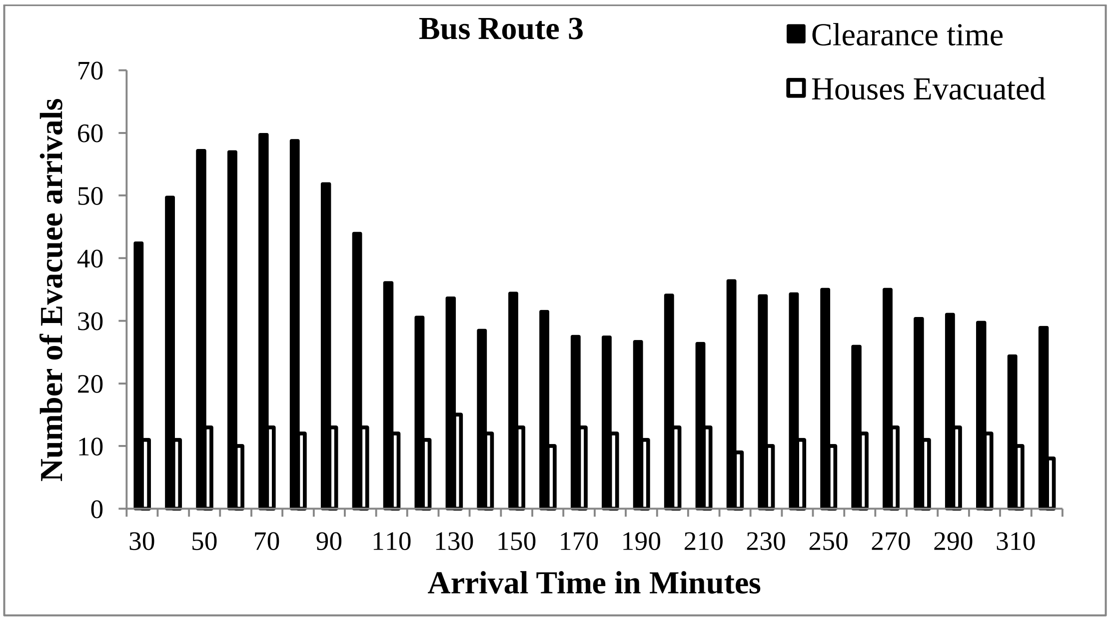


Figure 5.16 Evacuee arrival profiles in shelter and bus capacity utilisation for route 3

It can be observed from Table 5.21 that:

- The number of vacant trips was extremely high in route 0 and route 1. The last trip needed for completing evacuation in these routes was 13 and 8 and the subsequent trips (16 to 21) were vacant and hence could be re-distributed to major demand areas namely route 2 and route 3.
- The average clearance time was relatively higher for routes 3 and 0 than other two routes. The variation in clearance time value was very high in route 3. Table B-3 infers that the clearance time for route 3 was very high initially and decreased with the passage of evacuation.
- From evacuation response curves (Figure 5.10) and Table 5.15, it can be observed that 75% and 95% of car evacuation were completed within 93 minutes and 132 minutes, respectively. From the departure curves of car (Inset 1, Figure 5.10), it can be seen that 75% and 95% of departure occurs about 60 minutes and 85 minutes, respectively. Hence the volume of vehicles on road is considerably high in this time span, and this could have resulted in very high clearance time for Route 3. Beyond 110-120 minutes, the clearance time drastically reduces in Route 3. Other routes had considerably less impact on clearance time due to other evacuating cars.
- 90% of departures to bus pickup points occur within 60 minutes and 100% within 143 minutes. However, the evacuation response curve (inset 2, Figure 5.10) clearly indicates that there is large time gap between departure and completing evacuation and this corroborated with the average waiting time of 85.42 (Table 5.14). From the trip-sheet analyses, the mismatched bus demand and dispatching along routes 3 and 2 is attributed as reason for very high waiting time.
- Routes 3 and 2 had considerable overlap; this implies that the pickup points in these zones were highly serviced. Even then, the utilisation of bus seating capacity is very high (above 55/60) in route 2 and 3 (Figure 5.15 and Figure 5.16) in spite of overlapped routes. In bus roster if the vacant trips of route 1 and 0 are re-routed to 2 and 3, there is considerably high possibility of reducing waiting time for these households. This will also reduce the wastage of invaluable bus trips to the needy zones.
- Major evacuation bus route (route 3) that drops to Shelter S7 and S9 passes through the busy road segment (P8-J5) and the busy junction J5. Any reduction in traffic along this route by ‘stopping/diverting transient traffic’ in the evacuation window (as

concluded in Section 5.5) will also reduce the clearance time of evacuation buses and hence the waiting time of evacuees.

- Figure 5.13 to Figure 5.16 present the route-wise bus utilisation and vacant seats on various routes. As the buses ply to public shelters, the time series of bus ‘arrival to destination’ also indicates the arrival profiles of evacuees to public shelters.
- It can be observed from Table 5.20 and Appendix - B (Table B.1, B.2 and B.3) that some of the departure time had delays for the vehicles entering the loading point. The decimal value indicates delay time in minute for that trip.

In summary, ABM showed that single-run observations have low standard error on KPIs and hence robust for analyses. The zone-wise population data could be helpful for the transport planners to estimate the level of demand for bus in different zones. The dispatching could be in such a way that more buses are sent to the zones in need to reduce waiting time. When there are no or low waiting evacuees along a route (data obtained through CCTV or from personnel in the field), buses should not be dispatched along that route and instead diverted to routes with higher demand.

Not including unofficial channel would underestimate the percentage of houses warned and also reduce the departure time without factoring the 'time needed to inform neighbours'. ABM showed that the lower estimate of departure time will result in under-estimation of ET by 12 %. From scenario -2, it can be concluded that increase in transient vehicle traffic (low and high levels) reduces the evacuation speed by 8.4% and 14.2%, increases the clearance time by 21.9% and 46.8% and delays evacuation.

Combining the two policies namely re-routing of buses to ‘Routes 2 and 3’ from ‘Routes 0 and 1’ and ‘Stopping/diverting transient traffic in transient route - 3’ has scope for reducing waiting time for buses and also clearance time of buses respectively. These two policies could be included in the transport plan and the implementation of these policies during evacuation requires further investigation.

5.6 **Implications of various transport management measures**

The previous section illustrated the transport model using ERGO city. The architecture of the model is designed using coordinate files and models to facilitate customization to other cities by including road features like round-abouts, multiple lanes, flyovers, etc can be programmed further. Transport planners of 'Ocean City' in Maryland United States studied six combinations of altering lanes and evacuation routes as alternatives for Hurricane evacuation routes (Zou et al. 2005, Table 1, p146) and studied using simulation model for overall evacuation performance. Transport officials can use OR/MS model as a platform to test various response plans, and it was illustrated in scenarios (Section 5.5.1 to 5.5.3).

The following sub-section presents a brief note on 'transport management measures' with illustrations from literature which are available for transport officials for improving evacuation KPIs. These measures can be implemented further in the model for measuring its impact. As a part of transport preparedness, EMAs could identify measures relevant to their transport infrastructure and then use the model to understand its implication on the overall evacuation.

A. Testing the impact of vulnerability in transport infrastructure on the Evacuation effectiveness

In the Hollsvollur region of Iceland, there is a bridge near the Skogar Township along the major evacuation route. After the evacuation was complete during 2010 Eyjafjallajokull glacial flooding, this bridge was flooded with volcanic ash. In that evacuation instance, it did not affect the evacuees' safety but highlights the vulnerability of that bridge. During the Gjálp eruption in 1996, a bridge on Highway-1 on the Skeiðarársandur outwash plain was destroyed (Gudmundson et al. 2008, p.252). In similar circumstances, the vulnerability of transport infrastructure, namely road closures due to the disaster or road accidents, collapse of bridge, etc could be identified and tested using simulation models in order to

- estimate the potential delay because of such eventuality
- identify alternative evacuation routes based on relatively lower ET.

Such models have been used in the literature (e.g. OREMS) and the proposed model could be used to test such scenarios and experiment which is one of the key purposes of developing simulation models. The transport officials as a part of preparedness initiative could indentify such vulnerability in their transport infrastructure and then represent its impact as a 'new road network configuration'. The users of the model will have to input the coordinate file of the disrupted road network and also change the input setup settings (e.g. speed limitations on particular evacuation routes) as needed and then re-run the model. The performance metric (for example TET) from the initial condition could be compared with the disrupted road infrastructure condition to identify the potential impact. By having indentified the alternative routes, the previous procedure could be repeated to obtain the performance metric for each route combination, and this can be compared to identify the relative best option.

B. Testing the potential of using contra-flow routes during evacuation

Well-chosen 'contra flow' routing plans have been found to be helpful in increasing the available road capacity for evacuation thereby reducing the overall ET. It must be emphasised that the ability to implement contra flow plan on a particular route depends on the field conditions (e.g. no round-about or over bridges) as well as infrastructure namely accessible feeder roads along the contra flow route direction.

For example, the central district in the ERGO city has high-rise residential buildings, commercial establishments, as well as educational institutions. Being a high-population density zone that needs to be evacuated, the sudden surge of traffic in the road junction could be expected from the onset of disaster warning. As an illustration in the ERGO city, the lanes of the expressway bringing traffic towards the central district could be converted as a contra-flow as illustrated in Figure 5.17. Transport authorities could identify feasible contra-flow locations as well as routes and test the potential improvement in the overall ET using a simulation model.

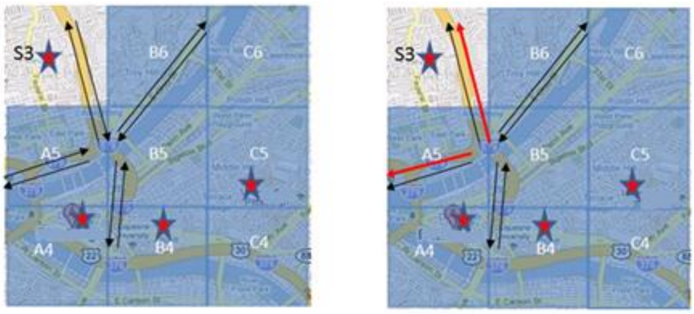


Figure 5.17 Snapshot of a contra-flow routing plan in ERGO city

C. Testing the capacity of public transport (e.g. buses) on evacuation effectiveness

The capacity of public transport will affect the number of buses available for evacuation and the transport officials could use simulation models to determine the implication of additional buses as well as their routing plan. The number of buses available with the public transport authorities could be enhanced by borrowing from the neighbouring regions and private companies. The capacity available with EMAs for response is limited and dispatching plans are pre-decided. The proportion of households choosing public transport for evacuation will increase pressure on bus operators to make round trips between pickups and destination, and possibly lead to longer bus waiting time. EMAs could identify the limiting proportion of bus users based on their capacity and dispatching plans and test their assumption using the model.

D. Identifying bottlenecks in the transport network

Transport planners will have information about bottlenecks in the road network by analysing the O-D data from operations centre, field data or by experience. The bottlenecks could be a road junction, a major expressway that could increase the overall ET. When context-specific transport elements are identified as critical/bottleneck using ABM experiments, day-to-day observations or experience, improving ET can be studied further. Having a model of the transport system enables such studies by the transport authorities.

For example, a transport plan might have contra flow of major expressways to have additional capacities. The contra-flow initiation point (Wolshon 2006, p29) might be critical for the contra-flow to function and it is possible to evaluate the designs using a simulation model. By identifying these locations for the city in the model and then analysing the evacuation KPIs of the evacuees through these points of interest, the planners will be able to know which among the locations will hinder more during evacuation and possible identify response strategies for the same.

E. Experimenting with the traffic signal system of the evacuated area to support evacuation.

Traffic signal timing is an adaptive response strategy for the transport planners during evacuation for dual purposes namely: a way of balancing the volume of traffic and prioritising roads in a junction in order to streamline the traffic. Managing ‘traffic signal units’ in continuous junctions in isolation rather than a system, will lead to sub-optimal ET because the signal phase length will be influenced by the volume of traffic in the connected road segments. On the other hand, by looking at the traffic signals along the same evacuation routes as a ‘system of individual units’, the authorities will be able to identify the signal length that minimises the overall ET and not only the ET of the connected road segments alone. The ABM model will be helpful for the planners to experiment different phase lengths of the traffic signal ‘simultaneously’ and obtain an optimal traffic signal strategy.

F. Impact of controlling the transient traffic on evacuation time.

Transient traffic is defined as the volume of non-local vehicles (vehicle/hour) using the expressway for a given time of the day. The transport authorities monitor this information for their day-to-day operation. In order to reduce congestion, "*spatial and temporal loading strategies of freeways*" (Wolshon 2006) was one of the transport policies. By diverting the transient traffic from the expressway, the authorities will be able to free the capacity available along the evacuation route. This will also avoid the vehicle entering the danger zone during evacuation. The proportion of transient traffic has been represented as an input parameter in the ERGO simulation model. Stopping/reducing transient traffic on select routes can be tested by the transport authorities to measure the impact on reducing the overall ET.

These are some of the diverse traffic management measures available for the transport planners to support evacuation and the simulation model serves as a platform for them to estimate the performance of these choices, leading to choosing relatively better response strategies.

Chapter Summary

In summary, this chapter begun with summarised ERGO findings related to evacuation traffic management followed by the development of model to support evacuation preparedness. The multi-modal agent-based traffic model provides a platform for the EMAs to test evacuee behaviour factors for the existing road networks. Impact of warning time and particularly the informal warning channel was tested using the model and highlighted the need for transport planners to work with warning dissemination agency for reliable departure data. As the means of transport is a household evacuation decision, the implication of it on the evacuation KPIs of the household and resources needed to support were studied using the model. Comparison of evacuation KPIs for three means of transport provided insights into the way of reducing the clearance time (for cars) and waiting time (for buses).

This model has potential to be used in plan evaluation, training transport officials as well in conducting exercise. The traffic management measures (Section 5.6) namely 'A-F' have not been implemented in this thesis and considered for future development of the model. On implementing these options as needed for the users, the model has stronger potential for in-depth testing of transport management options.

Limitations and Further scope of research.

The following are some key assumptions and limitations of ABM transportation model

1. Lane changing, overtaking and non-compliance to traffic rules (e.g. skipping red signals, violating speed limits) are not included in the model.
2. Travel behaviour (e.g. route, destination, etc.) is set at the time of departure and will remain unchanged in the model. Real-time traffic updates (e.g. digital signboards) and their influences in changing travel plan are not modelled.
3. A typical urban road networks will have over-bridges, round-about, tunnels, spaghetti junctions, etc. These features have been excluded from the transportation model as a simplification.
4. It is assumed that all the family members will evacuate together from their house. i.e. one car is used for evacuation per house.
5. Information about route is available to the evacuating household through media channels (e.g. news, internet, household evacuation plan, and evacuation plan of GOs).
6. Evacuating household decides the evacuation route prior to departure and do not change it after embarking.
7. Even though over-taking of cars happens during the normal traffic, it is assumed that the cars will not over-take, not exceed road speed limit and follow traffic regulations. These assumptions are based on the view that evacuees will comply with evacuation plans and traffic regulations. The level of compliance and the role of information in ensuring compliance were found to play a key role (Pel et al. 2011) and can be further researched by incorporating this variable in the model.

ABM transportation model was developed for three commonly used means of transport (car, bus and pedestrian). There are other context-specific 'means of transport' which are available and widely used in city-scale evacuation, but have not been included in this model. The overall KPI values will be different when these means of transport will also be included in the model, and this is a limitation of the model and its findings related to evacuation KPIs.

During evacuation there may be a possibility of accidents due to collision, vehicle break down and influence of real-time traffic information (such as traffic congestion, unexpected road closures, etc.) which can influence the evacuation route plan prior to departure and even change the plans after departure. These events will require revising the evacuation route. Pel et al. (2011) has presented a method to factor in the dynamic changes in route plans due to traffic information particularly for models that are executed only once. As a simplification, the dynamic route change is excluded as a simplification and the model assumes that the route is decided before departure remains unchanged. The likelihood of these disruptions needs to be estimated from the existing transport records or estimated with the help of experienced transport planner. The evacuation model needs further modification in order to know the impact of disruption during transit on the overall ET.

Driving behaviour modelling involves complex dimensions including profile of the driver, age, gender, personality factors, type of vehicle, etc. that affect 'response to stimuli' in a leader follower pair. In this thesis, driving behaviour has been modelled using two major factors such as desired speed and perceived safe factor. However, the impact of other factors requires further investigation.

Pedestrians were modelled using collision avoidance method (Karamouzas et al. 2009; Mas et al. 2012a) in a grid space. This thesis simplified that the pedestrians will not interact with the road network and also other pedestrians. The evacuation time is computed using walking speed and linear evacuation distance. However, the pedestrians do travel along groups and will influence the road traffic wherever there are pedestrian crossings in an urban environment. The simplified representation of pedestrians is a limitation of this thesis.

The 'car-following model' could be compared with empirical evidence (refer Ossen and Hoogendoorn 2011) to formulate representative parameter values for driving behaviour for various categories (cars, trucks and buses). For example, evacuation data collected from CCTV images, trajectory observations, etc are a useful data source. The video analyses of longitudinal driving data could provide reliable empirical evidence to the ABM. This thesis has adopted a simple car-following model with only two parameters namely desired speed and perceived safe gap. The choice of car-following model will have an influence on the accuracy of KPI findings from transportation model and this is a limitation for this thesis.

Situational or environmental conditions in the road network along with personality type are some of the key causes for aggressive driving behaviour (Laagland 2005, p2). There are various forms of aggressive behaviour beyond exceeding speed limits and running traffic signals during non-emergency circumstances. During large-scale evacuation with large number of evacuating vehicles, there are possibilities of some drivers displaying aggressive driving behaviour. Aggressive driving could risk the lives of self and others during evacuation/normal situation. Two major driver behaviour uncertainties were modelled in this thesis namely desired driving speed and perceived safe gap, and the primary goal of the drivers is modelled through 'anti-collision logic' by regulating two modelled variables. This thesis bases an opinion that the drivers display 'responsible' driving behaviour during evacuation as a simplification. The level of aggressive driving behaviour and its influence on non-aggressive drivers will be an interesting problem for further research and for which the ABM would be suitable.

As a large proportion of evacuating vehicles are going to depart in a short evacuation window, there is a possibility of the queue getting built up in major routes as the signal turns red. When the signal duration is longer, it is possible that that junction will become a bottleneck, resulting in reduced flow rate and congestion in the trailing roads. "*The longer the cycle length used, the better the performance in terms of the number of vehicles to escape in a given time period, but the worse the performance in terms of delay to vehicles on the minor roadways"* (Chen et al. 2007). The delays on the adjoining roads observed in this thesis corroborates with the observation made by Chen et al. (2007). This is similar to a bullwhip phenomena observed in a supply chain or a bottleneck moving upstream from the congested junction upwards to the roads that lead to it. The chances of cars built up can be reduced by choosing a, low-signal cycle time (duration of red) and have more number of green phase per hour. For the same overall green phase per hour, it is better to have as much short green signal duration than fewer long green phases.

Even though these learning were based on an illustrative case study in a single-lane multi-modal evacuation traffic system, the observations are argued as relevant to be further investigated even for complex multi-lane evacuation traffic system. Loading time into the evacuation bus is excluded. It can be recollected from Figure 5.8 that bus routes are designed to serve specific evacuation shelters. Figure 5.13 to Figure 5.16 present the route-wise arrival profiles of evacuees to their destination (public shelters). This data will be helpful for the shelter operators (ESF-3) to plan for the registration process and also know the trend of shortage/available accommodation. If the buses are re-routed to high demand routes, the waiting time will get reduced and the arrival profile will need to be re-computed. This again highlights the need for shelter operators to work closely with transport authorities for more evidence-based preparedness and design shelter allocation plans. Chapter 6 presents the third ESF i.e. shelter management.

CHAPTER SIX: MODEL DEVELOPMENT - SHELTER INFORMATION MANAGEMENT SYSTEM

6.1 Emergency Accommodation Management

The third ESF is managing the emergency accommodation for the evacuated public. In the recent 5.7 earthquake (September-2012) in Yilang County in Yunnan province China, around 100,000 people were evacuated. More than 20,000 houses were damaged or got collapsed (Rediffmail 2012). These evacuated residents were expected to need sheltering for weeks till their houses are rebuilt. During 'Cyclone Yasi' (February 2011) in Australia, over 400,000 resident populations were in danger. Based on the meteorological department's prediction of cyclone route, a large number of people needed mandatory evacuation as well as public sheltering. For unprepared EMAs, such situations could prove catastrophic, including loss of lives.

This chapter of the thesis has been organised into two sections. This first section summarises the key findings from the ERGO project on sheltering. The second section of this chapter presents the model development of 'Shelter Information Management System' (SIMS).

6.2 Key findings based on the ERGO project data

Data from various sources such as interviews, feedback visit, evacuation plans and practitioner reports were analysed in the ERGO project. There are various aspects in shelter management which came to light: '*who among the evacuees need shelters?, where and how large are the public shelters? And how are these shelters to be allocated to different evacuating zones?*' The mere identification of the shelters by the EMAs will not enable supporting the emergency accommodation during evacuation. The EMAs responsible for supporting the evacuees to identify a place of safety during the evacuated period can take a holistic approach to ensure preparedness. The following sub-section of this thesis will summarise the key findings into three different sub-topics, namely

1. Sheltering policies in the evacuation plan,
2. Sheltering location - capacity (where to shelter?),
3. Shelter demand (how many people will require sheltering?).

6.2.1 Sheltering policies in the evacuation plan

Across ERGO countries, there are various categories of shelters with different purposes identified during the project:

- 'Emergency aid centre', Rest centre or 'Reception Centre' (United Kingdom and Iceland), where evacuees will be registered for safe evacuation, providing information to the public and then taken to safety.
- 'In-sheltering' is widely used for flash flooding in Japan.
- Apart from flash flooding, the evacuees also need to evacuate (as pedestrians) to the neighbourhood community centre ('horizontal evacuation') for fire caused by earthquakes in Japan.
- During the data collection, it was observed that evacuating to higher floors within the same building ('vertical evacuation') was a widely used evacuation alternative in Germany, Iceland and Japan.

These categories, though referred using different names in practice, are similar to the classification presented by Xu et al. (2006, p182) based on duration of evacuation. In Japan, it is a legal obligation for evacuees to move to shelter by foot and cannot use cars in certain zones, and this policy has been communicated to the public in the preparedness stage. An evacuation public sheltering plan needs to identify various evacuation alternatives available for the planned threat.

6.2.2 Sheltering locations and capacity

Across the ERGO countries, it was observed that the local authorities in coordination with the Red Cross identify and operate the shelters. During the ERGO data collection, it was found that schools, community centres, public buildings, churches, indoor sports complexes, cinema theatres, gyms, farm houses, tourist homes and colleges were identified and used as sheltering locations.

Shelters (Fjoldahjalparsod) are identified by the local authorities in Iceland, and this information is shared in the 'Mt. Katla Volcanic eruption preparedness leaflets' (Figure 5.1) and communicated to the public. As per Iceland's evacuation plan, evacuees need to report to the 'emergency aid centre' and they will be moved to shelters from there. Some locations serve as both registration centre and a shelter.

Regarding the location of the shelters, the province of Liege (Belgium) has identified four potential locations for shelters around the Doel nuclear plant, but outside the inner zone. In case of eventuality, the inner zones will be evacuated to these identified safe locations. The scenario used for planning in London is the evacuation of parts of London to neighbouring boroughs, where the evacuees will be sheltered. During a fire accident in Denmark, the authorities decided to evacuate about 400 residents to a school within the neighbourhood. In few hours as the situation got beyond control, the sheltered evacuees needed to be evacuated to another place as the school building was within the danger area. These indicate variety of evacuated zones and the location of shelters.

During the evacuation due to volcanic eruption in Iceland (March 2010), this information was crucial as the evacuation needed to be completed within 30 minutes. The interviewed evacuees shared that they knew in advance 'where to go for evacuee registration'. During the evacuation, the specific shelter details are provided as a part of warning message in Doel Nuclear plant evacuation Belgium, as well as in Hamburg and Iceland. This practise of communicating details of shelters to the general public in the warning message makes it actionable during evacuation.

The emergency planning officials in the Harburg district in Hamburg have identified shelters in schools, gyms and public buildings. Additionally, they have collected details such as bed capacity, address and contact numbers of the people in charge of opening the shelter. This information was stored within the evacuation plan and will be helpful during evacuation decision. Each sheltering location will accommodate a limited number of people when they need to stay overnight. In this thesis, the number of people who can be accommodated in shelters will be referred to as 'capacity of shelter'.

All the shelters identified during planning may not be available during evacuation. Some reasons are due to direction of wind during a nuclear incident (Belgium), sheltered location may be within danger zone (Denmark) and the location could be in flooded area (Hamburg). The actual shelter capacity available may be less than the overall planned capacity. The EMAs will have a challenge of managing the sheltering needs with a reduced capacity during response. Thus, EMAs need to base the decision of 'which shelters to use' based on the prevailing circumstance, and the sheltering details collected at the preparedness stage will prove to be vital. In order for the authorities to identify and communicate available shelters during evacuation, it is important for consolidating/storing shelter details in an accessible database.

6.2.3 Demand for the public shelters

The province of Liege in Belgium has divided the potential evacuation zones into ‘sectors’ around the nuclear plant to facilitate easier communication of the evacuation zone to the authorities as well as to the residents. This will help in understanding the potential demand for shelters in each evacuated zone depending on the population and socio-economic factors. Estimating the number of people who require shelters (demand), though useful in aligning with the capacity, is challenging for the EMAs.

During a preventative evacuation for the detection of World-War – II bombs in East Flanders, about 330 people were warned and evacuated. Among them 70 residents (about 21%) went to public shelters and others evacuated to friends and family. During the volcanic eruption in Eyjafjallajokull in Iceland (March-2010) around 800 had to be evacuated, out of which 110 to 135 required accommodations (about 16.8%) on three evacuation instances (Shaw et al. 2011a, p258).

During interviews with the Ministry of Interior in Germany, an official estimated 10-20% as the shelter demand (Shaw et al. 2011a, p258). The interviews during ERGO project showed that there was no generalizable value for shelter demand and it varied between 3-20% (Shaw et al. 2011a, p258). Post-evacuation reports are one source of obtaining planning estimate for demand.

Apart from shelter location planning, there were various shelter operations support services found during the ERGO interview such as evacuee registration process, planning for decontamination capacity after a large-scale nuclear incident evacuation, psycho-social and medical support, Search and Rescue, etc. (Shaw et al p259).

In summary, the following are the key findings of this thesis on emergency accommodation.

- Alternatives available for evacuation such as in-sheltering, vertical evacuation and horizontal evacuation were widely used in many countries.

- It was found that shelters have been identified by the local authorities in various countries but not widely documented with capacity details to support the evacuation decision.
- Literature on evacuation shelter management highlighted that the socio-economic factors (Mileti et al. 1992) will influence the proportion of evacuees seeking shelter (shelter demand) among the evacuated population. Post-evacuation studies (Brodie et al. 2006) after Hurricane Katrina in the United States have indicated the highlighted high shelter usage by the 'ethnic minorities and immigrant population' and the people from low-economic strata. Mileti et al. (1992) has also provided estimates for public shelter usage for various types of disasters based on historical records. During the ERGO interviews, there was no evidence of explicit assumption about the impact of socio-economic factors on the likely shelter demand.
- Apart from resident population, tourist places requiring evacuation might have large proportion of tourists needing shelter. This need to be included while estimating shelter demand.
- There was no well-developed systematic practise among the ERGO countries on estimating the shelter demand and allocating the available capacity, and this topic requires further investigation.
- Providing information about the shelter locations and evacuation routes through a leaflet was well developed in Iceland, and this was found to be effective in the recent evacuation for glacial flooding (April 2010).
- Operating shelters with the help of NGOs like Red Cross is widely practised, but the logistics of managing lifeline supplies at a 'safe inventory level' and delivery of these items from warehouse to various shelters require further investigation. As this thesis is limited to the evacuees reaching shelters, this problem could be investigated in the future.

During mass evacuation situations involving many local authorities, the centralised decision-making team need to collate and allocate the shelters on a rational basis in-order to quickly move the evacuees to safety. This thesis will present a holistic approach in shelter information management and develop a tool that can help managing the public shelter information and allocation. There are various shelter allocation studies considering the allocation of shelters assuming the compliance of evacuees (Ng et al. 2010, Pel et al. 2011), but the implication of this assumption requires further investigation. This thesis investigates the implication of shelter choice behaviour on the allocation of available shelters.

6.3 **Shelter Information Management System – A holistic approach**

EMAs support evacuees in reaching safe locations during evacuation and 'Shelter management' is the last ESF. There are different destination options available for the evacuees to move to safety namely going to friends and family outside the evacuated zone, hotels or private accommodation and public shelters. This thesis has proposed a holistic approach for managing the shelter location information that will help the EMAs to effectively allocate shelters to different evacuating zones.

The SIMS tool proposed in this thesis will

i) Provide a platform for organised collection of data required for public shelters.

ii) Support in optimal allocation of the shelters to various evacuated zones.

The illustration of this tool will be presented in the next section using the ERGO city case study. Figure 6.1 presents the holistic approach proposed in this thesis which will be elaborated in the following paragraphs. In line with the other two ESFs, the model presented in this chapter for shelter management will be organised into preparedness tasks, analysis and response plans. At the outset, the inner dotted rectangle in the figure specifies the boundary of the SIMS tool. Tasks specified as the rectangles are to be carried out at the 'preparedness stage' by the EMAs to provide information for a particular step of the SIMS tool. Tasks specified in the oval boxes are the potential measures for the 'response stage' based on the allocation model of the SIMS tool. The following section elaborates the holistic approach in the order of using the SIMS tool.

Obtain zone-wise 'Shelter demand' [Step 1]

The number of evacuees seeking public shelters for safety for the duration of evacuation is referred to as 'Shelter demand'. The level of need for public shelters is primary information needed for shelter management. EMAs prepare an evacuation plan for a highly likely hazard or threat. The authorities identify potential evacuation zones for the planning scenarios by using computer models (Wright et al. 2006) specific to disasters (e.g. nuclear plume dispersion model). The demographic (e.g. resident population, number of houses and family details) and socio-economic (e.g. ethnicity and economic status) details about the public living in the region are collected at the preparedness stage, and this can be analysed further to obtain the zone-wise evacuee profile for the potential evacuation zones. GIS is a widely used tool for managing spatial information about the evacuation zone (Pal et al. 2009) and shelters.

There are various sources for obtaining evacuee behaviour data as elaborated in Chapter 3. Depending on the access to information and cost of data collection, EMAs can analyse the level of shelter usage data from varied sources, to name a few: *stated-preference surveys (FEMA 2010), post-evacuation reports (Brodie et al. 2006) and detailed cross-sectional studies of historical records (Mileti et al. 1992).* These studies provide guidance and evidence base for estimating the shelter demand as a function of independent variables like resident population, vulnerable population (elderly, public under medical care, etc.), tourists, proportion of ethnic minorities and people in the low-economic status. Humanitarian organisations such as Red Cross maintain records of shelter usage for their past evacuation, and this could serve as another source.

Each of these data source has its own reliability, as well as cost, and in the absence of any of these data sources the EMAs could estimate the demand for shelters by senior practitioner's experience. By identifying the potential evacuation zones for the planning scenario, the shelter demand can be estimated for each zone based on socio-economic details. This estimate will serve as key information for the Step 1 of the proposed SIMS tool.

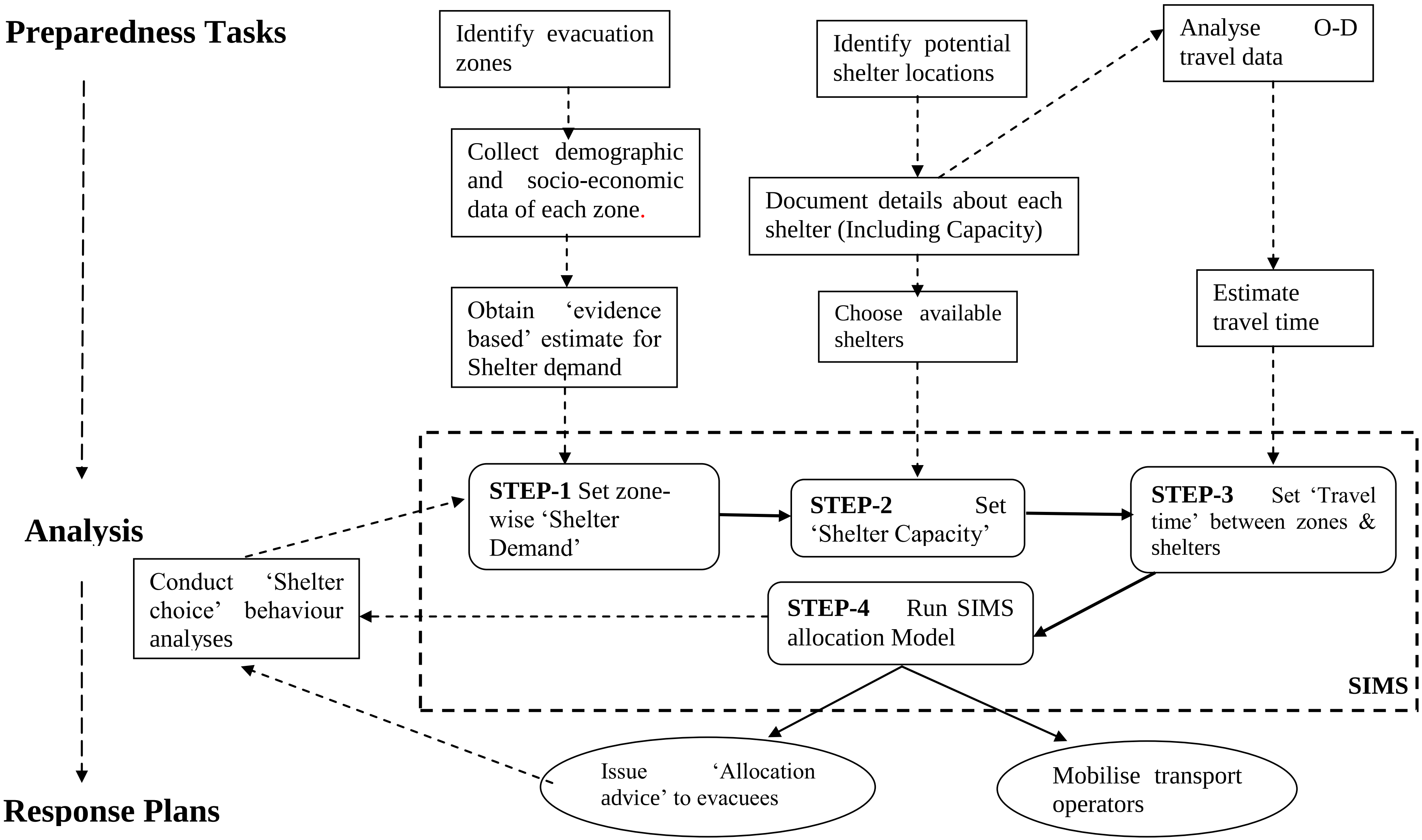


Figure 6.1 Holistic approach to shelter management and the role of SIMS tool

Ascertain 'Shelter capacity' [Step 2]

Data collection showed that, there are various public buildings and schools used as potential location for shelters. Each of these facilities can accommodate only a fixed number of evacuees and this is referred to as 'shelter capacity'. This is important data for managing emergency accommodation. Not all the buildings may be suitable for sheltering evacuees for many days. For example, though a warehouse can accommodate many beds when empty, without lifeline support (e.g. enough number of toilets) it will not be suitable as shelter. Kar and Hodgson (2008, Table 3, p235) presented a broad classification of facilities that are candidates for identifying shelters among potential buildings. This study has also developed a multi-factor method based on weights for prioritising shelter features and selecting suitable shelters using a GIS tool. In another study, a GIS system was used to identify the optimal location for building shelters for river flooding in India (Sanyal and Lu 2009).

Shelter buildings are generally identified by the local authorities and documented in the evacuation plan. Apart from documenting the accommodation capacity, details such as address, telephone contact details, owner or single-point-of-contact, etc. can be documented in a systematic way across all the local authorities. This has been practised in Hamburg Germany, as tables within the evacuation plan. This thesis argues that developing a template in 'spreadsheet software' can facilitate standardisation of practise across the regions. When the shelter details are stored in an organised format, this information can be easily analysed to know the shelters in the safe neighbouring areas to receive evacuees. It is easier to mobilise a coordinated effort, when 'the shelter details (including capacity) along with the spatial information' (location, address, contact details) are stored in computers such as spreadsheets or GIS map, instead of tables in the evacuation plan.

A shelter may not be suitable for all disasters. For example, a building may be suitable for flooding due to high ground level but may not be structurally safe for sheltering during tornadoes. Likewise, a shelter can become unavailable during a disaster. For example, a shelter facility may be along the nuclear plume direction. By overlaying the location details of the shelters on a flood inundation map, the suitable shelters can be identified. A similar approach has been illustrated in Kar and Hodgson (2008). EMAs can adopt such an approach by overlaying the locations of shelters in their disaster models to know the potential vulnerabilities. By verifying the ground realities during evacuation, only the shelters that are safe and available are to be considered for evacuation by the decision makers. Apart from the building details of each shelter, the capacity of shelter and spatial location details will serve as a key input for the Step 2 of SIMS tool.

Compute 'Travel time' between zones and shelters [Step 3].

The zones to be evacuated are identified based on the disaster impact. The potential demand of public shelters can be estimated at the zone level [Step 1]. Shelters are buildings with specific capacity located in the regions receiving evacuees. The spatial distributiveness of the evacuation zones (sources) and the public shelters (destinations) will lead to movement of traffic towards the latter. There are various means of transport used by the evacuees such as cars, public transport and as pedestrians, and the time required to reach the shelter will vary accordingly. For example, Stern and Sinuany-Stern (1989) developed a behavioural simulation model considering various means of evacuation for different times of the day. As the emergency accommodation is defined as a place of safety for days, it is assumed in this thesis that the evacuees will evacuate to shelters using cars to carry their personal belongings needed for few days, and the travel time using cars will be computed accordingly.

Results from the transportation model (Chapter 5) showed that, the travel time or clearance time for evacuation is the lowest using cars, followed by public transport (buses) and the slowest evacuation is by foot. During disruption in the road network due to traffic congestion or accidents, it might take longer to evacuate in cars. This thesis adopts the travel time using cars as a representative value from the evacuated zones to the shelters. The simplified assumption of evacuation using cars is an optimistic scenario for planning, and the uncertainty in the travel time will be an interesting topic to be explored in the future. EMAs can develop scenarios for evacuation (e.g. day-time versus night-time) considering the volume of traffic on roads (Stern and Sinuany-Stern 1989), leading to a various travel time scenarios between the evacuation zones and shelters. Here, the transport models with behavioural components as presented in the Chapter 5 can help in providing reliable planning estimates for travel time to the shelter managing authorities, and this further corroborates the interconnectedness of ESFs.

The 'travel time' estimates can be obtained from various sources depending on the intended accuracy of the results as well as on the availability of data.

i) Transport officials will be able to provide an estimate of travel time based on O-D studies. These are collected for day-to-day operation as well for traffic management during evacuation. O-D data are widely used in the evacuation transport models for example OREMS (Southworth 1991).

ii) Evacuee transport models will be another source of travel time data by obtaining the values for a planned scenario.

iii) In the absence of these, the EMAs can collect approximate travel time values from websites (e.g. maps.google.com) and then scale them by an appropriate congestion factor.

The estimated travel time between the potential evacuation zones to the shelters will serve as a key input to Step 3 of the SIMS tool.

Run SIMS Allocation model [Step 4] and Analyse allocation Results [Step 5]

The mere identification of shelters will not complete the role of EMAs in providing shelters to the evacuees. It has been found that evacuees choosing the shelters by themselves will lead to sub-optimal ET (Ng et al. 2010). Detailed information about the number of evacuees from each region as well as the capacity of each shelter is available only with the EMAs and not with the public. The overseeing authorities need to allocate the shelters by balancing the evacuees of all the regions (demand), the available capacity at each shelters and the time needed to reach the shelters. There are various allocation models proposed in the existing literature (Sherali et al. 1991, Kongsomsaksakul et al. 2005, Ng et al. 2010) but the implication of household choice behaviour on evacuation performance is yet to be investigated. This thesis investigates the impact of 'evacuee shelter choice behaviour' using a generalised formulation for optimal allocation of shelters.

Using the SIMS tool, the users can input the evacuation zone details, shelter information, and the travel time for the chosen scenario and run the model to obtain optimal shelter allocation results. Comparison of estimated demand for public shelters and the identified shelter capacity can indicate any potential shortages. A detailed presentation of the allocation model and subsequent behaviour analyses is presented in Sections 6.3.2 and 6.3.4, respectively. Once the zone-wise shelter allocation is available, the EMAs can develop localised preparedness materials such as leaflets that indicate the shelters and evacuation routes. For example, 'Mt. Katla Volcanic eruption preparedness leaflets' (Figure 5.1) prepared by Iceland; and New-Hannover county's multi-hazard preparedness website and map (NHC 2010) are very good examples. It is important for the local authorities to generate awareness about the shelters at the preparedness stage and the results from the SIMS model will support EMAs with the allocation details.

Apart from supporting the planning of shelter management, outputs of the model can provide guidance for response strategies in implementing the allocation results.

a) First, the authorities during response can develop zone-specific warning messages with the respective 'shelter allocation advice'. The model output can serve as a reliable evidence base for developing public preparedness leaflets and campaigns. This will persuade the public to consider moving to the allocated shelters.
b) Second, the overseeing authorities can mobilise transport facilities for taking the evacuees from the evacuated zone to the allocated shelters. Section 5.14 presented bus routes to pick up evacuees from zones to public shelters and scope managing arrivals based on vacancy available was elaborated in the third scenario.

These two tasks are illustration of developing response plans based on the analyses from the SIMS tool. This concludes Steps 4 and 5 of the SIMS tool.

It can be observed that the tasks outside the SIMS (indicated by dotted lines) are a research field in itself with a considerable body of knowledge, and this thesis contributes in proposing a holistic approach of integrating multiple sources of data in order to better manage evacuation shelters. The SIMS tool proposed in this thesis provides a structured approach and a platform/aid for the practitioners to organise relevant information, share with regional authorities and enable further in arriving at optimal shelter allocation policies. It can be observed that the supporting data for shelter management are obtained from very diverse sources (e.g. O-D data are collected by transport planners), and for effective management of shelters there is a pressing need for multi-agency collaboration, or at the least to have access to these information for the overseeing authority.

6.3.1 Purpose and scope of the model

The previous section of this chapter presented the holistic approach for managing shelter information. The SIMS tool usage will be illustrated below with the ERGO city case study. The model has been developed for collecting the key information about public shelters in the planning phase of evacuation. There are other key details about shelters such as owner of the building or single-point-of-contact, address, contact number, etc. These can also be collected for each shelter to quicken the opening and running of shelters. The spreadsheets can be easily customised based on the available information.

In general, MS-Excel spreadsheets are widely used for organised management of data. This thesis assumes that MS-excel spreadsheet is relatively familiar and easier environment for the EMAs, leading to potential adoption of SIMS tool and hence MS-Excel has been chosen for developing this tool.

6.3.2 Illustration of SIMS tool using ERGO city case study

The following section illustrates the usage of SIMS tool for the ERGO city case, and it is argued that the proposed holistic approach is generalisable to any other city. As discussed in the earlier chapter (Section 3.3.5), there are 19 zones to be evacuated indicated by blue zones in the following ERGO city map (Figure 6.2). There are shelters identified in advance throughout the ERGO city by the local authorities. Due to the level of flood in the evacuated zones, the shelters within that zone are deemed as unsafe. The shelters available in the neighbouring 10 boroughs (represented by Star symbol S1-S10) are available for receiving the evacuees.

As there are 19 evacuated zones to be accommodated in 10 boroughs with shelters of different capacities, the decision maker at the regional level need to collate the information at a centralised place. Considering the overall ET of all the evacuees, the EMAs responsible for shelter need to arrive at optimum allocation policy, and in this context the model proposed by this thesis will be able to support the decision makers. The users of this model will be required to enter the details in five steps and run the model in order to obtain optimum allocation results. The screenshot of the main page of SIMS model is presented in Figure 6.3.

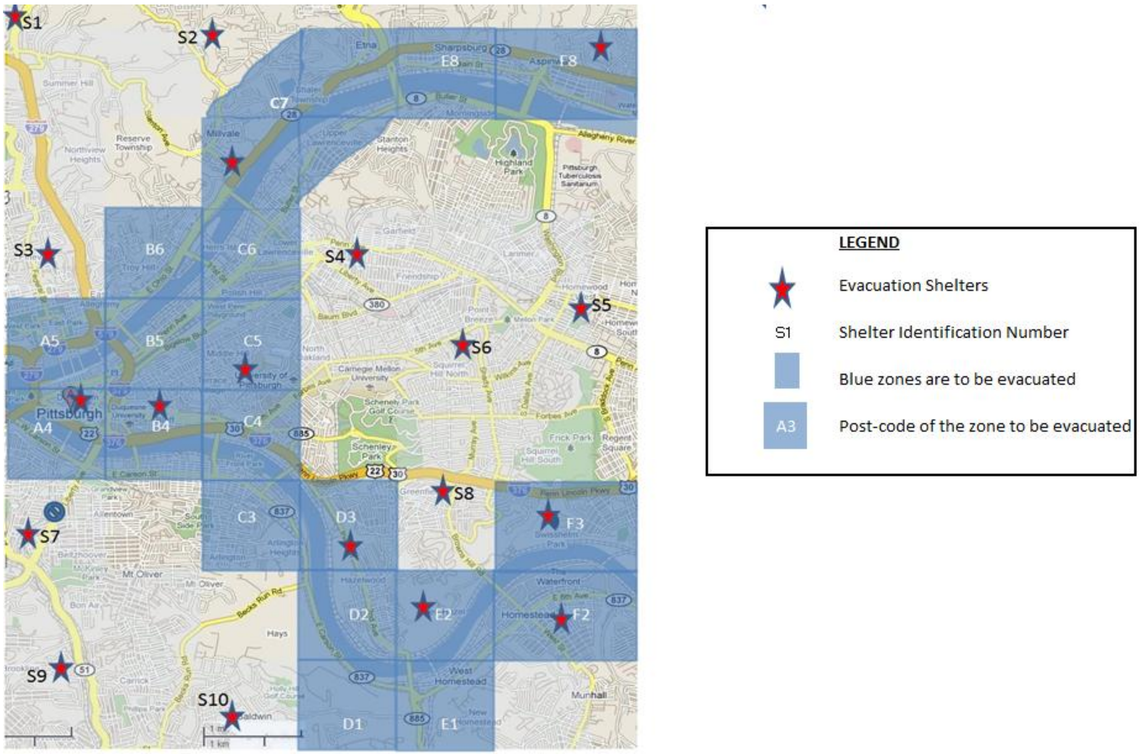


Figure 6.2 Shelters and evacuated zones in the ERGO city

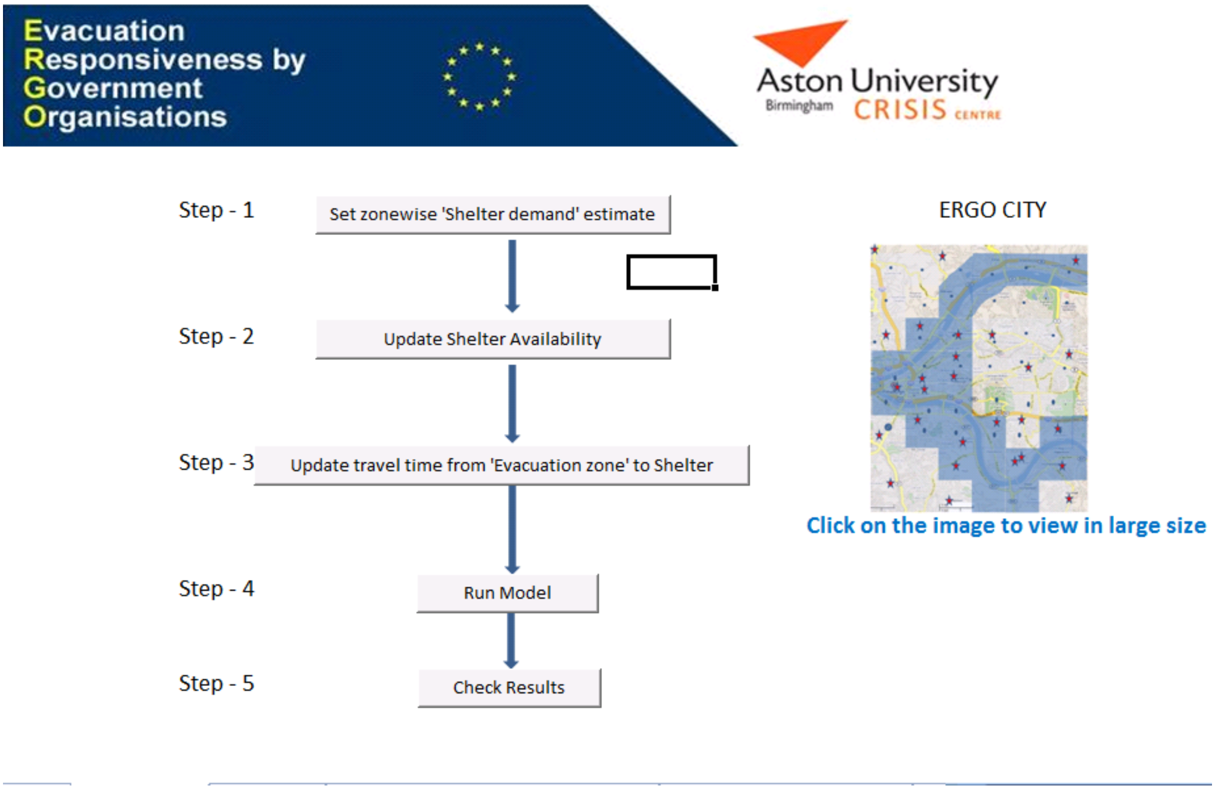


Figure 6.3 Screenshot of Shelter Information Management and Allocation System

PostCode	Evacuation Area	Population	Shelter-Demand
D1	Churchview Ave Exd, Allegheny	3750	300
E1	Gates Dr	4375	350
D2	Mansion Street, Hazelwood	10000	800
E2	Johnston Ave, Hazelwood	5625	450
F2	Ravine Street, Homestead	5000	400
C3	Josephine Street	5625	450
D3	Sylvan Ave, 15207	6875	550
F3	Olivia Street, 15218	8750	700
A4	Liberty Bridge	11250	900
B4	E Carson Street	9000	800
C4	27th Street, 15203	12000	850
A5	McCrea Way, 15222	12500	1000
B5	22nd Street, 15222	9375	750
C5	Herron Avenue, 15219	11000	950
B6	Gardner Street, 15212	8625	500
C6	35th Street 15201	7500	600
C7	Heth's Playground	10000	800
E8	River Road, Sharpsburg	7000	650
F8	E Waldheim Road, 15215	7500	700

Total	155750	12500
Average % of evacuees per zone	8.03%	

Figure 6.4 Details of the evacuated zones and estimated demands for shelter (Step-1)

Step 1 is to collect the population details of the evacuated zone grouped using different postcodes along with the estimated demand for shelters. The EMAs could use socio-economic data to arrive at this estimate along with their experience of managing previous evacuations. The total demand for shelters was found to be 12,500 for 19 evacuated boroughs on an average of 8% of the population. Figure 6.4 summarises the shelter demand for the evacuated zones.

Step 2 is to collate the information about available shelters from neighbouring boroughs. It can be observed (see Figure 6.2) that the local authorities have identified suitable buildings as sheltering locations in advance within their evacuation plan. Some of the shelters within the evacuated zone (blue squares) are unavailable. There are two key data required about the shelters:

i) Number of evacuees accommodated in each shelter and location (Step 2)

ii) Travel time for each available shelter from each evacuated zone (Step 3)

Figure 6.5 presents the summary of available shelters along with their capacity. Figure 6.6 shows the travel time matrix (in minutes) for the combinations of various evacuated zones and available shelters. For each origin (zone) and destination (shelter) pair, the travel time values were computed using the website www.maps.google.com for evacuation using cars. Alternatively, the output of the transportation model can be another data source.

Shelter-id	PostCode	Address	Location/Type	Capacity
S1	A8	Brethaur St	School	770
S2	C8	Haser Road	Sports Complex	1740
S3	A6	Fineview	Fineview Neighbourhood Center	470
S4	D6	Bloomfield	Exhibition Center	650
S5	E5	Hobart Street, Squirrel Hill South	Squirrel Hill Community Center	880
S6	F5	Homewood playground,	Sports Complex	2750
S7	A3	Climax Street,	University Accomodation	1650
S8	E3	Windsor St,	School	690
S9	A1	Eben Street	Indoor Stadium	2600
S10	C1	Elm Leaf Park	Baldwin Community Center	700
			Total available capacity	12900

Figure 6.5 List of shelters available and its details in the ERGO city (Step 2)

	Shelter									
Zone	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
D1	37	36	36	28	28	33	27	21	20	12
E1	36	35	38	28	28	33	27	21	25	16
D2	34	33	31	25	25	30	25	18	20	17
E2	33	32	33	25	25	30	25	14	25	20
F2	36	35	37	25	25	30	28	18	30	22
C3	34	33	25	22	22	27	20	18	17	17
D3	34	33	26	21	21	26	20	14	20	20
F3	36	35	33	24	17	22	28	14	32	23
A4	32	31	17	19	24	27	14	28	20	23
B4	32	31	19	17	22	22	14	24	21	23
C4	31	30	20	19	24	20	19	19	22	23
A5	29	28	14	19	24	27	17	32	25	28
B5	29	28	17	18	23	22	19	28	26	29
C5	27	27	20	15	20	20	22	23	27	29
B6	25	28	14	18	23	22	24	33	35	34
C6	25	25	17	15	20	20	25	28	36	35
C7	23	20	20	17	22	20	28	19	37	37
E8	25	23	24	19	24	18	36	24	38	40
F8	28	25	30	19	24	18	38	26	40	38

Figure 6.6 Estimated travel times (in minutes) from the different evacuated zones to the available shelters (Step 3)

Figure 6.7 summarises the data of the ERGO city shelter allocation problem. When the capacity available for allocation is more than or equal to the estimated demand, then the authorities will be able to arrive at optimum allocation using the allocation model. *How does the model allocate evacuation zones to shelters?* This is discussed in the next section. When the estimated demand exceeds the total available shelters, the model will allocate to the available capacity. In such a situation, the EMAs need to identify alternative avenues for accommodating the excess evacuees.

Number of zones to be evacuated	=	19
Total evacuees who need public shelter	=	12500
Number of public shelters available	=	10
Total number of evacuees who can be accommodated in public shelter	=	12900
Is there a shortage of shelters?	=	No

Figure 6.7 Summary of ERGO city shelter allocation problem

6.3.3 Generalised formulation of shelter allocation model

Having collected the information in the SIMS tool about the potential shelters and estimated the demand using a holistic approach, the centralised team need to have strategies for allocating the shelters. The interactive nature of SIMS tool will enable the authorities to update the unavailable shelters due to the disaster impact or inaccessibility. The following section of this chapter presents the generalised formulation of the shelter allocation model. The formulated model serves as a basis for allocating shelters as well as subsequent analyses of shelter choice behaviour.

Let there be 'n' zones to be evacuated to 'm' shelters. Let 'i' be the variable indicating the evacuated zone and 'j' indicates the allocated shelter. Let X_{ij} represent the 'decision variable' indicating the numbers of evacuees from zone 'i' to be allocated in the shelter 'j'. The evacuation travel time for each evacuee from zone 'i' to the shelter 'j' is represented using the variable T_{ij}. The proposed model will allocate the evacuees from different zones based on the objective of minimising the overall ET (i.e. sum of ET for all the evacuees from evacuated zones to the allocated shelters). This has been widely used in the existing shelter allocation models (Sherali et al. 1991, Kongsomsaksakul et al. 2005, Ng et al. 2010). This objective function is represented mathematically as follows:

$$Min\ Z = \sum_{i=1}^{n} \sum_{j=1}^{m} X_{ij} T_{ij} \tag{6.1}$$

Shelter allocation is influenced by two aspects, namely the demands for shelters from each evacuated zone and the availability of shelters. Each of these is represented as constraint as given below.

Constraint -1: Demand constraint (for each zone)

The allocated shelters for zone 'i' should either equal or exceed the estimated demand represented as D_i. There will be one constraint for each zone to satisfy the estimated demand of evacuees from the zone. The following equation is an illustration for zone – 5 and followed by a generalised expression.

$$\sum_{j=1}^{m}(X_{5j}) \geq D_5$$

In general,

$\sum_{j=1}^{m}(X_{ij}) \geq D_i$ For all i = 1,2,3…n evacuated zones. (6.2)

Constraint – 2: Shelter capacities (for each shelter)

The number of evacuees allocated to a shelter 'j' from all the zones should not exceed the shelter capacity represented as S_j. There will be one constraint for each shelter to limit the allocated evacuees from all the zones. And this has been illustrated for shelter – 3 and followed by a generalised expression.

$$\sum_{i=1}^{n}(X_{i3}) \leq S_3$$

In general,

$\sum_{i=1}^{n}(X_{ij}) \leq S_j$ For all j = 1,2,3…m available shelters. (6.3)

By solving the allocation model, the decision variables (X_{ij}) represent the optimum shelter allocation results and the EMAs will be able to interpret the results as described in Chapter 8. This shelter allocation model will serve as a basic platform to further investigate the impact of varied shelter choice behaviours on the ET. Figure 6.8 summarises the generalised formulation of the shelter allocation model.

Decision Variable

X_{ij} = Optimal allocation of evacuees from the zone 'i' to the shelter 'j'.

Objective Function To minimise the overall evacuation time of all the evacuees (Z)

$$\boldsymbol{Minimise}\ Z = \sum_{i=1}^{n}\sum_{j=1}^{m} X_{ij}T_{ij}$$

Subject to

$\sum_{j=1}^{m}(X_{ij}) \geq D_i$ For all i = 1,2,3,…n evacuated zones. [Evacuee demand constraint]

$\sum_{i=1}^{n}(X_{ij}) \leq S_j$ For all j = 1,2,3…m available shelters. [Shelter capacity constraint]

$X_{ij} \geq 0\ and\ X_{ij}\ is\ integer \quad where\ i = 1,2,\dots n\ and\ j = 1,2,\dots m$ [Integrality constraint]

Figure 6.8 Formulation of shelter allocation model

As the decision variables are integers, and the objective function and all the constraints are linear, the formulation of the problem indicates an 'Integer Programming' (IP) problem structure. The suitability of the choice of the method has been elaborated in Section 3.3.4.

The flooding scenario is used for illustration that results in the evacuation of 19 zones and with estimated shelter demand varying between 300 and 1000 with a total of about 12,500 evacuees. There are about 10 shelters in the neighbouring communities with 'total accommodation capacity' of 12,900 evacuees. The shelter allocation problem was formulated and the SIMS model was run (Step 4) to obtain the optimal allocation as given in Table 6.1

Table 6.1 Zone-wise shelter allocation results obtained from the SIMS allocation model

		SHELTERS										
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Total
EVACUATED ZONES	D1										300	300
	E1										350	350
	D2									800		800
	E2								450			450
	F2					110			240		50	400
	C3									450		450
	D3									550		550
	F3					700						700
	A4							320		580		900
	B4							800				800
	C4						630			220		850
	A5			470				530				1000
	B5						750					750
	C5				280		670					950
	B6	500										500
	C6		160		370	70						600
	C7		800									800
	E8		650									650
	F8						700					700
Total Allocated		500	1610	470	650	880	2750	1650	690	2600	700	12500

The total evacuation time (TET) for these evacuees was about 231,630 minutes with an average household level ET of 18.5 minutes. It can be observed that some of the evacuation zones are allotted to more than one shelter and vice versa. Overseeing authorities can run such analyses for various evacuation planning scenario and severity of threats where the % evacuees to shelter (demand) varies. Apart from organising the required information for allocating shelters, EMAs can implement the results from SIMS tool in the following ways.

- Communicate to each local authority of evacuation zones, their corresponding 'allocated shelters' for overseeing evacuation.
- Evacuation preparedness materials such as leaflets were prepared specific to each geography in Hamburg, Iceland (Figure 5.1) and New-Hannover County (NHC 2010). For example, while preparing the leaflet for C6 zone, the allocated shelters namely S2 and S4, S5 can be specifically mentioned to encourage evacuees to choose these shelters. EMAs could also design 'allocation message' template to be used during evacuation.

- Some evacuees may need public transport for evacuation. Local authorities in collaboration with bus operators can organise buses from the pick-up points in different zones to the allocated shelters. This will streamline the number of evacuees to allocated shelters and indirectly increase the allocation-advice compliance percent. For example, the evacuated zone A5 (McCrea Way) with estimated shelter demand of 1000 evacuees will be allocated to two shelters namely Fineview (S3) and Climax Street (S7) about 470 evacuees to S3 and 530 to S7, respectively. Assuming the capacity of bus to be 60 passengers, the authorities could send six buses between A5 to S3 and seven buses between A5 to S7 respectively.
- Coordinate with the transport officials in ascertaining optimal evacuation routes for different zones to the allocated shelters. This 'evacuation routes' can be indicated in the preparedness leaflets similar to NHC (2010).

When all the evacuees comply with the shelter allocation advice, though ideal, it will lead to optimal evacuation in the shortest possible time (ET = 18.5 minutes). In reality, there are uncertainties in the sheltering choice, leading to some evacuating population showing non-compliance behaviour (NCB). The following section presents the impact of uncertainty on allocation effectiveness.

Apart from presenting a SIMS tool based on a holistic approach, this thesis investigates the effect of shelter choice behaviour of evacuees on the allocation. Thus, the IP model formulated in this section will serve as a 'simulation test bed' for quantifying the implication of shelter choice behaviour of the evacuees. The existing 'excel solver' in MS-office 2007 can handle utmost 200 decision variables in an optimization problem and in the case of ERGO city it is 190 (19 zones and 10 shelters). Moreover, the formulation of shelter allocation model is generalisable to any number of evacuation zones and shelters combinations. When this limit of 200 is exceeded, the users need to use some other 'IP solver' for obtaining optimal allocation, and this is a limitation of developing SIMS tool in the MS-excel 2007.

6.3.4 Impact of the evacuee shelter choice on shelter allocation

The objective of shelter allocation using IP formulation was to minimise the overall ET and subsequently the EMAs issue evacuation advice to respective zones. Not all the evacuees may follow the allocation message issued by the officials. Evacuees may choose the shelter as a personalised choice (e.g. closer to workplace) which could be different to the allocated shelters. Findings from the ERGO data collection did not indicate any allocation models considering the evacuee choices currently used in practice. There are three main approaches for allocating shelters in the existing literature, namely:

i) Assuming that the evacuees will follow allocation advice (Sherali et al. 1991) and solved as location-allocation problem from the EMA perspective.

ii) As a bi-level allocation model, at the first level the EMAs will allocate from the overall evacuation and in the second level evacuees will choose a convenient choice (Kongsomsaksakul et al. 2005).

iii) A hybrid model (Ng et al. 2010) of evacuation of combining system optimal behaviour of evacuees (cooperative behaviour) as well as the selfish behaviour of evacuees (non-cooperative behaviour).

Will uncertainty in behaviour impact the overall ET and disrupt operating the shelters? This thesis investigates the impact of evacuee shelter choice on the overall success of evacuation. The shelter choices of evacuees will be discussed in more detail to identify various behaviour classes in the next sub-section. The last sub-section presents the approach adopted in this thesis for performing the 'sensitivity analyses of these behaviours' on the evacuation time to shelters.

Behaviours of evacuees in choosing shelters

Shelter allocation policies and the advice inherently assume a certain level of compliance of the evacuees to the shelter allocation. During a post-evacuation interview in the Iceland after Mt. Eyjafjallajokull eruption, an evacuee recollected that the 'information meetings' heightened the awareness of shelters and evacuation routes. The household reported to have evacuated to the allocated shelter for their zone. Such 'compliance behaviour' (CB) cannot be generalised to all the evacuees. Such an assumption is an ideal case resulting in a more 'organised and controlled evacuation' with lowest overall ET.

When the evacuees receive the warning message, believe it and choose to evacuate with the family members, there are various factors that will affect their destination choice. Some proportion of evacuating population will choose private accommodation for sheltering and the remaining may require public shelters. Mileti et al. (1992) presented a synthesis of meta-analyses from historical data on the role of socio-economic and demographic factors of the evacuees in choosing public shelters. The household level preferences will lead to different behaviours in choosing a particular shelter among the available.

Apart from the preparedness leaflets and the household evacuation plans, the news updates in the media such as television, radio as well as internet will provide real-time information about the emerging disaster situation. This will have an influence on the shelter choice of the household. When the threat is rapid and imminent, the nearest shelter is a more convenient choice. When a household decides themselves on which shelter to go, some of them might choose the 'nearest shelters', as that will require shortest evacuation time to safety. Such behaviour is referred in this thesis as 'selfish choice behaviour' (SC). SC behaviour is modelled in this thesis by selecting a shelter that has the shortest travel time for that zone.

During the day time some members of the household may be in their workplace away from the evacuated zone and possibly choose a common meeting point and mutually convenient shelter for evacuation. Other evacuees may choose a convenient place or known locality. As shelters are generally public buildings, some shelter may have more relative appeal than others. For example, an indoor stadium with lifeline as well as recreational facilities may be more appealing than a community building. Based on their 'personal choice' (PC) an evacuating household might choose a shelter, and this has been modelled in this thesis using a random distribution function.

The behaviour at the 'household level' (SC or PC) need not be in-line with the allocation advice which is chosen as an optimal policy at the 'overall city level'. The priorities at the household level (as presented above) may be different from the EMA's perspective. EMAs have information such as the capacity of each shelter and estimated demand for each zone. On the other hand evacuees do not have this information and possibly might choose a shelter other than the allocated shelters. Thus from the EMA preparedness perspective, the evacuee shelter choice behaviour has two broad categories namely 'compliance behaviour' (CB) and 'non-compliance behaviour' (NCB). CB is modelled in this thesis as an evacuating household who will follow the EMA's optimal allocation advice.

Considering all the evacuating zones and with the objective of ensuring everyone's safety, when EMAs allocate shelter they will aim at maximising the overall evacuation success. As there will be travel time required from the danger zone to the 'allocated' shelter based on the distance as well as on the average speed of evacuation, the authorities will be able to allocate shelters by minimising the TET from zones to shelters as elaborated in 6.3.3. This thesis will use the generalised formulation as a basis for measuring the sensitiveness of shelter choice behaviours.

6.3.4.2 Design of Experiments for measuring the impact of uncertainty in evacuee behaviour

As elaborated in the previous sub-section, there are three behaviours namely SC, PC and CB. The behaviour of all the households in the evacuating region will fall into one of these three categories. NCB has two components namely PC and SC. In an extreme situation, a city can comprise of evacuees choosing using SC (SC = 100%, PC = 0%) or PC (SC ~ 0%, PC ~ 100%). Such an extreme value for non-compliance behaviour (NCB ~100%, CB~0%) is a possible case where the trust in the authorities and their preparedness initiatives is abysmally low, leading to extreme non-compliance. On the other hand, an assumption of all the evacuees to comply with allocation advice (NCB ~0%; CB ~100%) is ideal. In reality, the aggregate behaviour of evacuees can be expected to be in the middle range of purely non-compliance to compliance behaviour. As the shelter choice will affect the successfulness of shelter advice and response plans, this uncertainty in the behaviour is investigated further by conducting sensitivity analyses. The three behaviours can be within the following closed range (includes the boundary values).

Selfish choice behaviour → SC ~ [0, 100]
Personal choice behaviour → PC ~ [0, 100]
Compliance behaviour → CB ~ [0, 100]
Non-compliance behaviour NCB = PC + SC (6.4)

The 'integrality condition' represented in equation 6.5 restricts the values of CB and NCB such that the overall behaviour of all the evacuees is aggregated within these two behaviours.

$$CB + NCB = 100\% \quad (6.5)$$

The experiment of behavioural uncertainty is designed as a discrete and repetitive process. An experimental set of aggregate behaviour is represented as {SC, PC, CB} subject to satisfying the equations 6.4 and 6.5. A discrete step size for behaviour is chosen as 5%, as this thesis assumes that anything lower than this may not be measurable in reality within a reasonable cost. For each of these variables complying with the conditions mentioned above, a shelter choice behaviour is sequentially obtained as an experimental set.

As this thesis will investigate the impact of uncertainty of sheltering behaviour on the shelter allocation, the ET becomes a logical output metric which is the basis for 'optimal' allocation in the generalised formulation. Apart from the overall evacuation time (TET), the components of household level ET with different behaviours will be helpful to quantify the relative sensitivity of the behaviours. The average evacuation time of the households with SC, PC and CB behaviours is represented using ET_{SC}, ET_{PC} and ET_{CB}, respectively. For a particular aggregate behaviour, the allocation is done sequentially.

1. A household is chosen randomly to have SC behaviour from different evacuating zones and the demand from the zone is reduced by one unit. For each of the zones, the nearest shelter is identified, and this is used to allocate the selected household's shelter. Subsequently, the shelter capacity is reduced by one unit. This step is repeated such that SC% of evacuating population has SC behaviour. ET_{SC} (travel time to the nearest shelter) is collected at each iteration in order to obtain the SC component of overall evacuation time (TET_{SC}).
2. After adjusting the demand and capacity for SC behaviour, a household is chosen randomly from the remaining houses in different evacuation zones and then allocated to a random available shelter. The demand for the selected zone and the capacity of the selected shelter is reduced by one unit. This step is repeated such that PC% of evacuating population has PC behaviour. ET_{PC} (travel time to the randomly selected shelter) is collected at each iteration in order to obtain the PC component of overall evacuation time (TET_{PC}).
3. After further adjusting the demand and capacity for SC and PC behaviours, the remaining demands from evacuation zones and the remaining available capacity in the shelters are used in the generalised formulation to obtain optimal allocation. This optimal allocation is used to set evacuees with CB. The SIMS model will provide the overall evacuation time of the evacuees with compliance behaviour (TET_{CB}).

For a particular set of behaviours (SC, PC, CB), the performance metrics such as household level average ET and the overall evacuation time components are collected. By running the SIMS models repeatedly, the experimental results will be further analysed to obtain generalisable conclusions. The value of CB is interdependent on the value of other two behaviours (100% – NCB = 100 – SC – PC). Thus, a 'behaviour-performance frontier' can be plotted for the independent 'behaviours' (SC and PC) on the X-axis and Y-axis and the dependent 'performance' metric (e.g. Overall ET) on the Z-axis. Figure 6.9 presents the flow chart of steps for obtaining 'behaviour-performance frontier'. By generating different valid combinations of (SC, PC and CB), the above procedure (Figure 6.9) is repeated to obtain TET and Average ET. Behaviour-performance frontier is drawn for TET and ET respectively in Figure 6.10 and Figure 6.11.

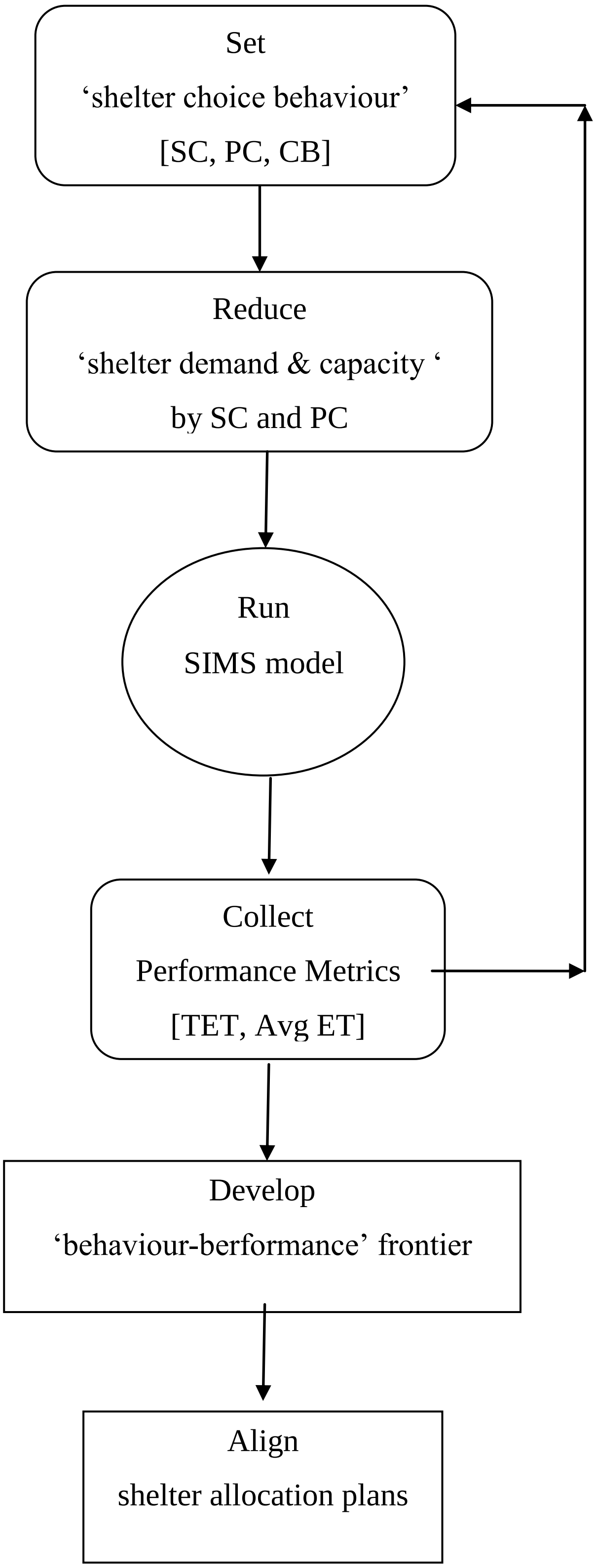


Figure 6.9 Flowchart of steps in developing 'behaviour-performance' frontier

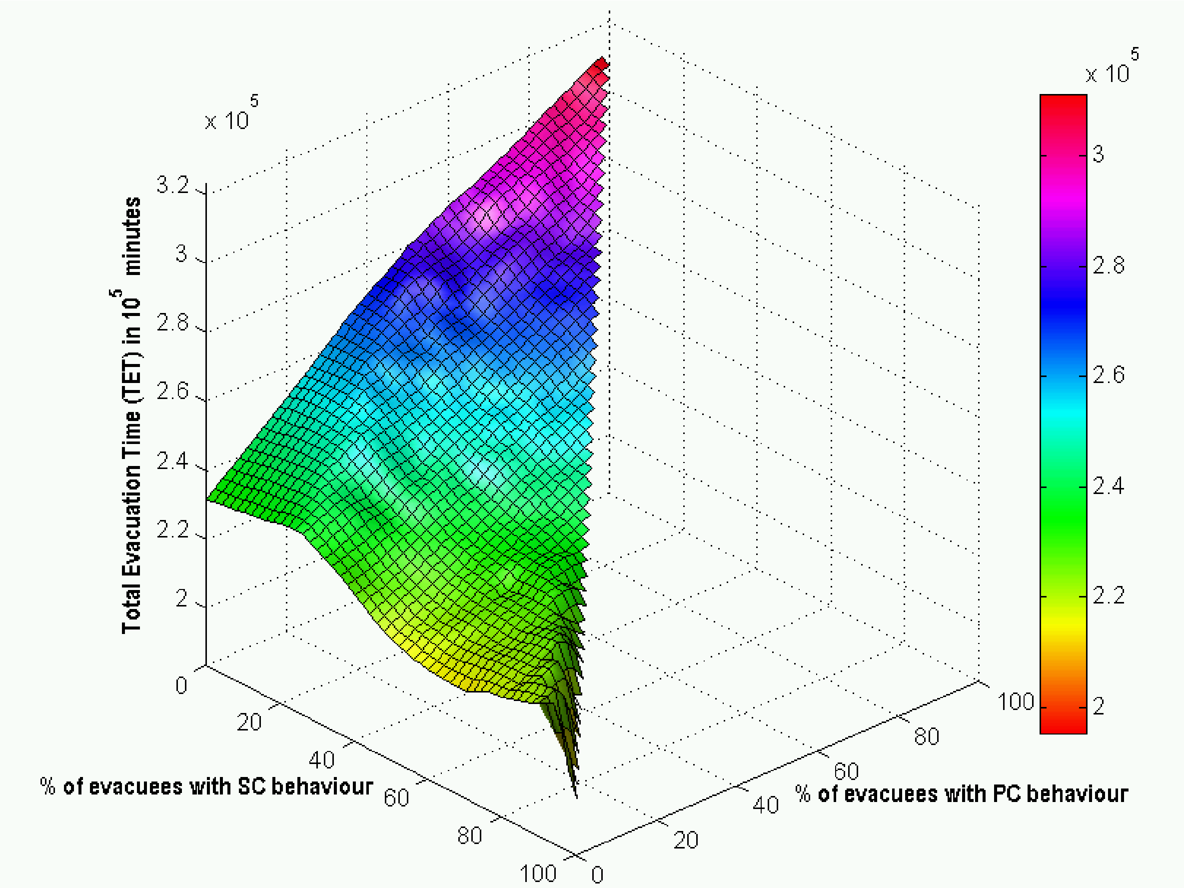


Figure 6.10 Sensitivity of non-compliance behaviours (SC, PC) on TET

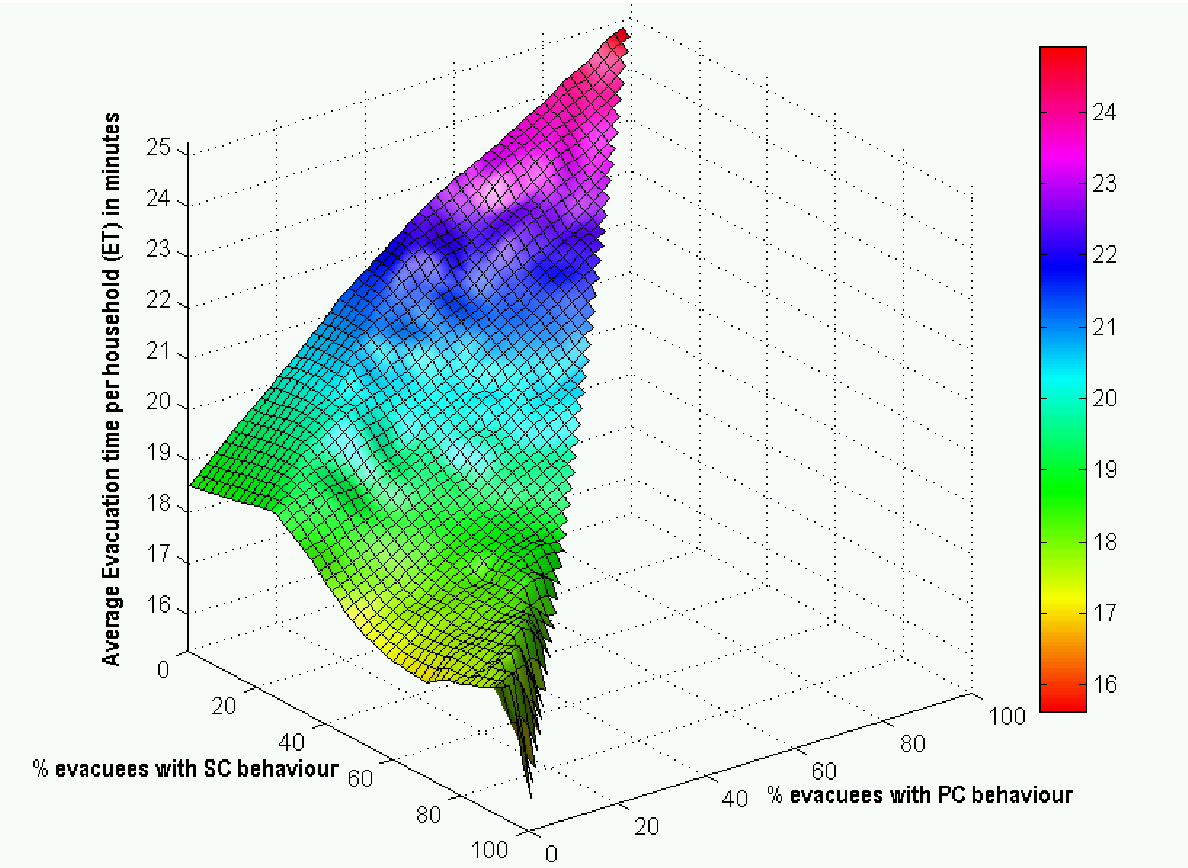


Figure 6.11 Sensitivity of non-compliance behaviours (SC, PC) on ET

The following are key findings from Figure 6.10 and Figure 6.11:

- The minimum (optimum) value of ET is when the behaviours of households are within SC is within 40 to 60%, CB is within 40 to 60% and PC is 0%. At this optimum range the household average ET is around 17 minutes.
- When PC is in the region 0 and 30, ET value is around 18.5 minutes.
- When PC is in the region 30 and 60, ET value is around 20 minutes.
- When PC is in the region 60 and 80, ET value is around 22 minutes.
- It can also be observed that PC behaviour has a higher impact on ET compared to SC.

Beyond a particular value of NCB, the evacuees will reach shelters without vacant places, and on the other hand some shelters will remain largely unoccupied. These evacuees may have to relocate (referred as hopping) to another vacant shelter on direction by the staffs with their own vehicle or by a pooled transport facility (e.g. bus). This would mean additional expense of transportation and time to reach safety due to non-compliance behaviour of the evacuees. For instance, during the preventive evacuation due to Cyclone Yasi in Australia (2011), an electronic media report indicated that the shelters were full and "*Police blocked desperate people trying to get into overcrowded shelters in north-eastern Australia*" (Taylor 2011b). Though this is an evidence of one occurrence, the authorities proactively needed to anticipate and prepare response strategies for better management of evacuating population. 'How can EMAs manage the redistribution of excess evacuees to vacant shelters?' 'What does it mean to the overall shelters operation?'

These require further study, and the sensitivity analyses from the model results can provide some guidance on this issue. This corroborates the need for generating awareness about the suggested shelters at the preparedness stage and providing enough information during the evacuation, thereby building trust with evacuees leading to more compliance to shelter allocation advice. GOs need to take a systemic view on understanding the implications of evacuee behaviour as well as managing the existing shelter capacities.

Number of evacuees reaching a non-vacant shelter who need to be relocated to a vacant shelter is referred to as hopping. For illustration, the 'level of hopping' needed has been presented for a particular combination of household behaviour {SC = 15%, PC = 70%, CB = 15%} in Table 6.2 and the results from the optimal allocation are presented in Table 6.3

.

It can be observed from Table 6.3 that the total number of evacuees to be relocated is 2480. The shelter S3 has about 30% of evacuee arrival beyond the capacity. Totally, there are five shelters (S1, S3, S4, S8 and S10) with evacuees who need to be relocated to vacant shelters. Three shelters (S2, S6 and S9) have vacancies. Table 6.4 summarises the shelters with excess evacuees and shelters with vacant capacity.

Table 6.2 Model results for (SC = 15% PC = 70% CB = 15%)

Shelter	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Total**
Capacity	770	1740	470	650	880	2750	1650	690	2600	700	12900
No. of NCB evacuees arriving at this shelter	901	871	1228	1293	871	1051	1050	1225	1022	1113	10625
No. of evacuees to be relocated	131	0	758	643	0	0	0	535	0	413	2480
Available capacity	0	869	0	0	9	1699	600	0	1578	0	

Table 6.3 Optimal allocation of the remaining evacuees with compliance behaviour (CB = 15%) using the model

		SHELTERS										
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Total**
EVACUATED ZONES	**D1**											
	E1											
	D2									171		171
	E2											
	F2											
	C3											
	D3											
	F3					9	63					72
	A4							107		190		297
	B4							151				151
	C4						195					195
	A5							342				342
	B5						99					99
	C5						342					342
	B6											
	C6											
	C7		134									134
	E8											
	F8						72					72
Total Allocated			134			9	771	600		361		1875
Total vacant		0	735	0	0	0	928	0	0	1217	0	2880

Table 6.4 Relocation of evacuees from non-vacant shelters to vacant shelters

Shelter	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Total**
Excess evacuees	131	0	758	643	0	0	0	535	0	413	2480
Available capacity	0	735	0	0	0	928	0	0	1217	0	2880

Three shelters (30%) were under-utilised and five shelters (50%) were over-crowded in the above example. This was due to independent shelter preference of the household conflicting to the overall allocation as planned by EMAs. The dynamics of the household preference for 'nearest shelter, convenient or random choice' and shelter capacity management needs further investigation. The relocation of evacuees (hopping) is also an allocation re-distribution problem that can be formulated as an IP with objective of reducing total relocation time. The network of hopping shelters is as indicated in Figure 6.12.

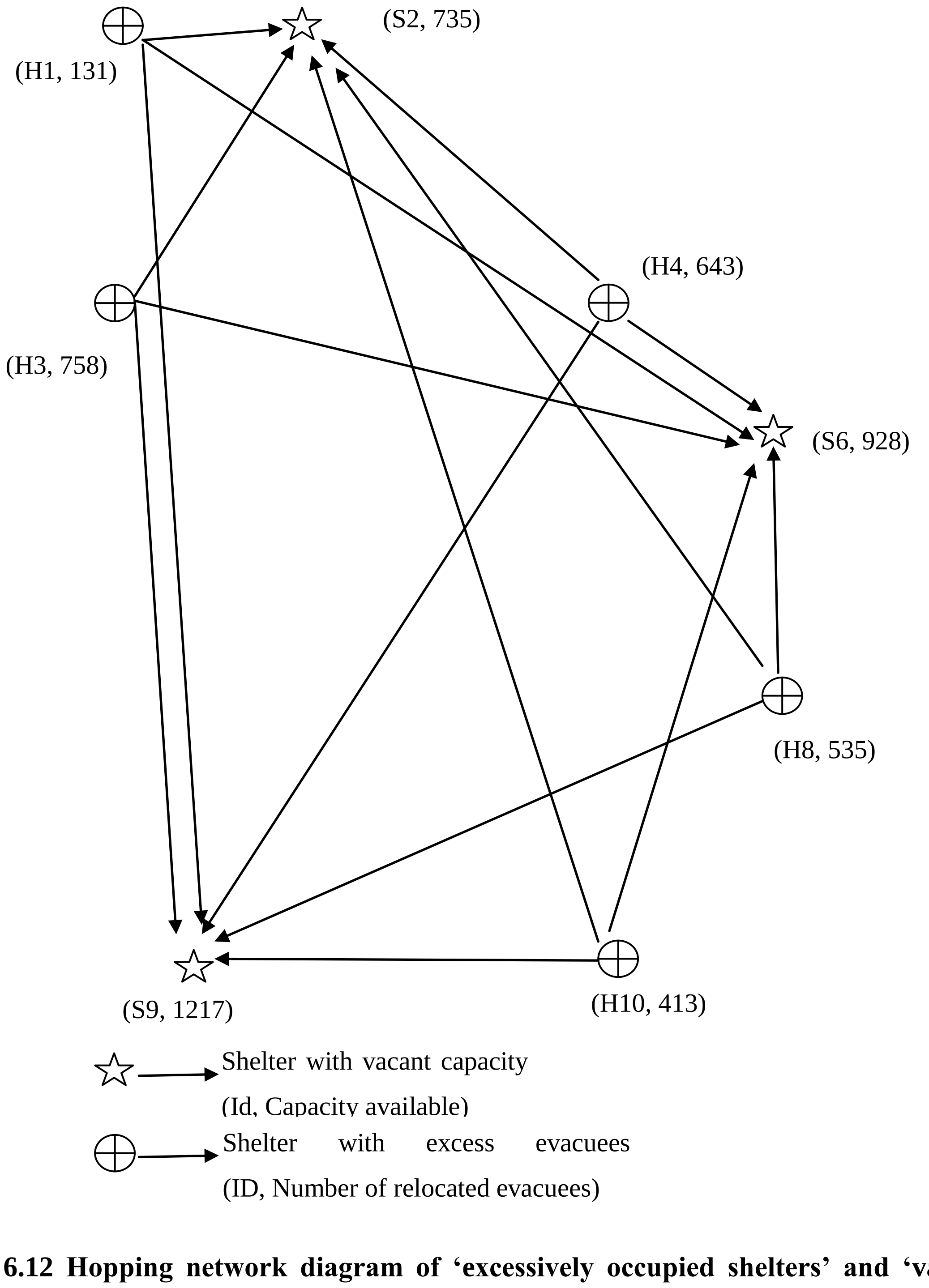


Figure 6.12 Hopping network diagram of 'excessively occupied shelters' and 'vacant shelters'

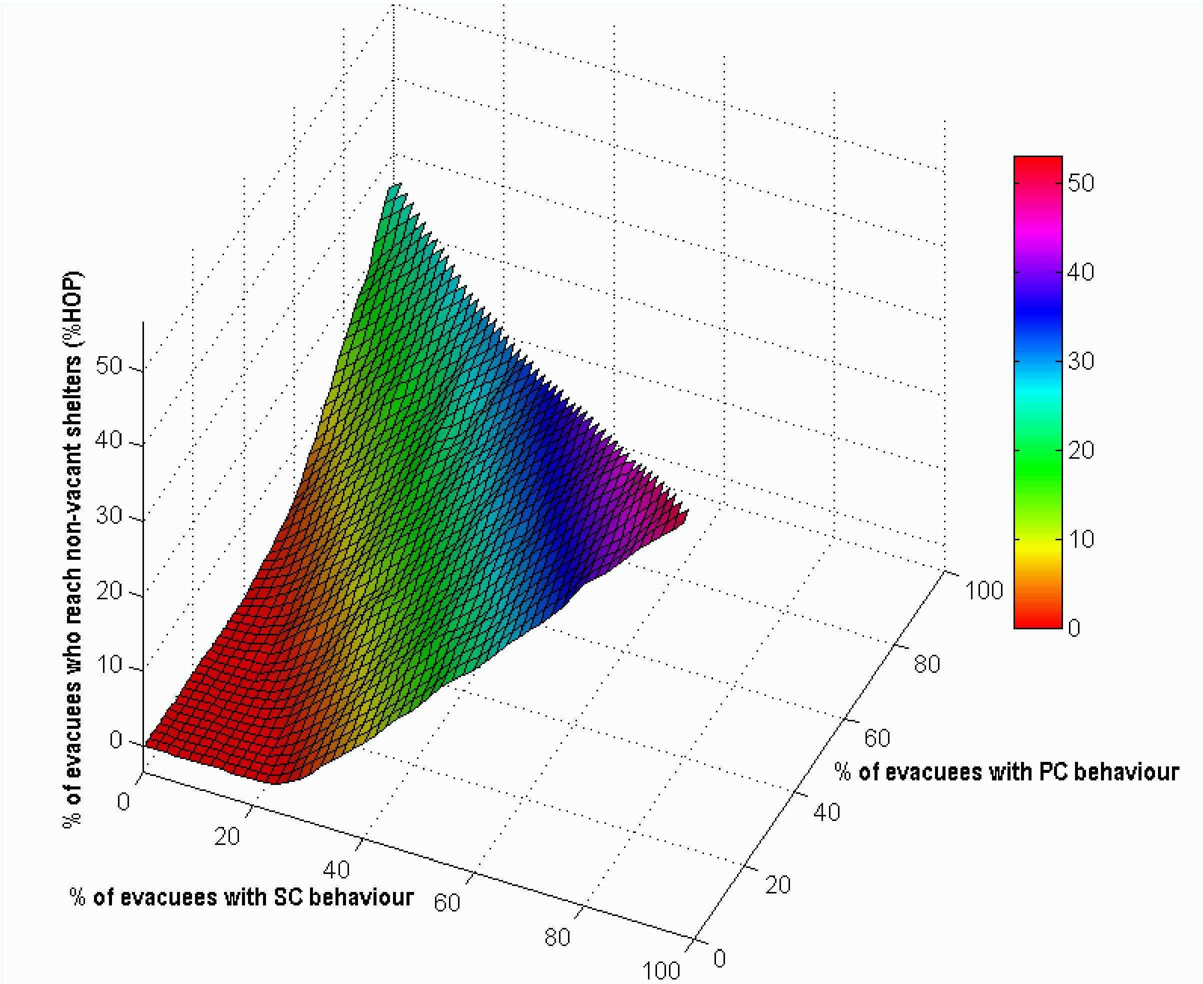


Figure 6.13 Impact of non-compliance behaviours (SC, PC) on the evacuees reaching non-vacant shelters (HOP)

From Figure 6.13, it can be observed that

- When the household behaviours are in the region {SC <=30%, PC <=40%}, the level of hopping is lowest and below 5%.
- When the household behaviours are in the region {SC <=40 to 60%, PC <=40 to 60%}, the level of hopping is about 20%.
- When all the households choose their nearest shelter (SC around 100%, PC =0%, CB = 0%), i.e. SC, the level of hopping is highest about 50%.
- It can be concluded that the sensitivity of SC behaviour is high above 60% and can influence overall shelter allocation.

As mentioned earlier, the hopping relocation is also a transportation problem. Shelters with excess evacuees and vacant shelters are indicated with prefix S and H respectively. On solving this optimization problem to finding an optimum redistribution of the hopping evacuees, Table 6.5 contains the results of the optimum redistribution.

Table 6.5 Optimum re-distribution of 'hopping evacuees'

	SHELTER		
HOP	S2	S6	S9
H1	131	0	0
H3	604	154	0
H4	0	643	0
H8	0	131	404
H10	0	0	413

In conclusion, this thesis proposed SIMS holistic approach for managing emergency accommodation as a preparedness initiative for ESF-3. The second section of this chapter studied the uncertainties in household behaviours, its impact on allocation policy and the level of hopping. The chapter concluded with re-distribution of hopping evacuees to available shelters in an optimal manner. Overall, this highlights the application of ORMS methods such as IP and sensitivity analyses for managing ESF-3.

The evacuation preparedness leaflet distributed in Iceland contains routing plans to the shelters and was found to be effective. Providing enough information (e.g. routing plans) and supporting evacuees to move to shelters (e.g. sending buses from evacuated zone to allocated shelters), the authorities will be able to influence the behaviour. The traffic conditions during evacuation and transport management measures (ESF-2) will affect the travel time value, which is a key input in shelter allocation (ESF-3). Any delay in warning the public (ESF-1) will have a cascading delay in evacuees reaching to safe shelters. This further corroborates the need for an integrated approach to evacuation planning as advocated by this thesis and will be presented in the next chapter (Chapter 7).

CHAPTER SEVEN: AN INTEGRATED MODELLING APPROACH TO EVACUATION PLANNING

The first section of this chapter summarises ERGO findings on the usage of analytical models for evacuation preparedness in two categories namely disaster-specific models and strategic planning models. The inter-relationship among the variables among ESFs has been established in the previous three chapters. The second section synthesises the inter-relationship among ESFs using consolidated results from the three models. Subsequently, integrated modelling approach is defined and elaborated in the last section of this chapter.

7.1 ERGO findings on 'the usage of OR/MS models for evacuation planning'

Research question 4 is "*How OR based approach can help GOs in evacuation planning*?" (in p31). Previous chapters presented the summary of conclusions from the three ESFs and the respective use of analytical models used in preparedness. Apart from ESF models, there are other tasks in the planning phase that can be supported using OR models. Chapter 2 classified the analytical models into two groups: 'disaster-specific models' that help in identifying the zones to be evacuated as well the time when it will strike and 'strategic policy planning models' that help the policy makers to evaluate the strategic decisions as well as helping the EMAs to evaluate response options. This sub-section of the chapter summarises along these two categories the application of analytical models, modelling technique and the country where it is used based on the ERGO project findings.

i) Disaster-specific models:

These are simulation models that study a specific threat. Most of the models under this categories deal with natural disasters (flooding, tsunamis) and nuclear threat. These models are mainly used to identify the areas affected during the disaster. During ERGO interviews it was found that EMA in Hamburg, Germany, has a flooding model (Shaw et al. 2011a, Figure 8.28). It is a GIS-based hydrological simulation model that helps in identifying the areas likely to be inundated.

Japan has the Owase tsunami wave propagation model (Shaw et al. 2011a, Figure 8.29) that estimates the likely number of fatalities during a tsunami. Iceland uses a meteorological model to evaluate avalanche risk. Sweden and Belgium have models to estimate the hazard zone (plume area) in the case of a release of radioactive material. Norway developed the 'Severe Nuclear Accident Programme' to model the plume behaviour and plan for large-scale nuclear incidents like Chernobyl. The Netherlands have developed an integrated model for evacuation traffic management for flooding disasters to simulate potential failures of dyke protection structures. Depending on the planning hazard, EMAs can investigate the relevant models further to explore the potential use in their evacuation plans.

ii) Strategic policy planning models

These models are used for planning response strategies and resource allocation. For example, the United Kingdom developed a simulation model to analyse the implications of centralising or decentralising resources to respond to three simultaneous major emergencies happening in the country. Belgium use an Excel model to estimate casualties and plan a response to large incidents e.g. aircraft accidents, accidents at music concerts. Iceland used ABM transport model of evacuation only with cars to estimate ET and bottleneck in the system. Table 7.1 summarises the models found in the ERGO countries, as well as models from other parts of the world.

i) Innovative use of models to generate awareness with the public:

A tsunami simulator and earthquake simulation platform are available in the Bosai Disaster Centre in Shizuoka (Japan) with life-size visuals and audio demonstration. This provides an opportunity for the public who have not experienced the disasters to raise their awareness, risk perception and be more prepared. Awareness of a nuclear emergency among the public could be generated in Belgium and Sweden by using a 'simplified form of computer model' to illustrate the evacuation plan to the public. Flood level simulator was used in Hamburg during an exercise to provide experiential learning of possible flood levels in tanks for the public living in inundation areas. The success of using models to generate awareness about glacial flooding in Hollsvollur region in Iceland was evident from the interviews after the Mt. Eyjafjallajokull eruption in 2010. These innovative applications of the OR model indicate an additional purpose, namely generating awareness with the public. The following section presents the consolidated results the ESF models developed in this thesis.

Table 7.1 Models used for mass evacuation preparedness

Sl. No.	Purpose of the model	Classification	Modelling Technique	Country
1	Flood and tsunami wave propagation models	Disaster specific models	GIS and multi-agent simulation	Germany, Japan, UK, Netherlands
2	Snow avalanches	Disaster specific models	Meteorological model	Iceland
3	Disaster viewer (earthquake relief planning)	Disaster specific models	Web-based GIS tool	Developed in UK, used around the world
4	Nuclear plume dispersion models to ascertain hazard zone	Disaster specific models	Meteorological model	Sweden
5	CAMHIE – Dispersion modelling system	Disaster specific models	GIS and Meteorological model	Belgium
6	Estimation of casualty in case of aircraft accidents, large events (music concert) and planning for the response.	Strategic policy planning models	Excel based simulation tool	Belgium
7	Mathematical model for policy making (Wein et al. 2009)	Strategic policy planning models	Optimization	USA, Netherlands
8	Resource allocation for simultaneous incidents	Strategic policy planning models	Discrete event simulation	UK

Sl. No.	Purpose of the model	Classification	Modelling Technique	Country
9	Operations in planning mass decontamination	Strategic policy planning models	Discrete event simulation	UK
10	Mass warning messaging service through mobile telephones	Warning dissemination models	Commercial product (Domino, Gedicom)	Belgium
11	Area and location based emergency warning system (landline, mobile)	Warning dissemination models	Commercial product (Unified Messaging Service)	Norway
12	Public announcement system (PA) for coverage of evacuation warning message	Warning dissemination models	Map with coverage details	Japan
13	Traffic congestion management	Traffic management models	Agent-based model and network model	Iceland, Spain and Japan

7.2 **Consolidated results from Evacuation models**

Zone-wise consolidated table of model results will be helpful to understand the need for zone-level multi-agency planning and has been presented in Table 7.2. Information about the demographic of evacuated zones such as number of houses, population, number of vehicles owned and location are needed commonly across the three ESFs. It can be observed from the table that the population is not the same across the zones. Zones D1 and F2 have about 14% each out of the evacuated households (5142). The total population of these two zones alone is 7290 out of 25,744 evacuated households, and hence the demand for ESFs (e.g. evacuation bus) is higher. EMAs require an understanding of population distribution in the potential evacuation zones.

Warning time depends on various factors as elaborated in (ESF-1) Chapter 4 and mainly ‘warning channel characteristics, access to the channel and role of informal channels’. Average warning time of the evacuated households is uniform across the evacuated zones. Zone ‘A4’ has 15.17 minutes slightly higher than other zones and overall average was 12.39.

The household’s departure time values are dependent on whether the informal warning time is included or otherwise. This serves as a linkage between ESF 1 and 2. Departure time, means of transport and destination are household decisions that play a key role in household's ET. In addition to these, driving behaviour of cars, transport policies on regulating traffic and dispatching evacuation buses to various routes influences overall evacuation KPI values.

It can be observed from Table 7.2 that the number of car users is very high in the highly populated zones namely D1 (514 houses) and F2 (526 houses). It can be observed that ‘average clearance time’ for car users in D1 was 44.18 minutes compared to other zones. The loading point for D1 is along the busiest road network J1 to J5. As only one loading point is present in each zone, the queue at D1’s loading point during departure would have been longer, leading to higher evacuation time.

In spite of having lower than average clearance time (27.04 minutes), zone C3 had the highest ET. The waiting time for buses was very high for this zone about 233.1 minutes which increased the overall evacuation time. Following C3, the zones D1, D2, E2 and F2 with high number of car users had very high average ET such as 120.44, 109.63, 103.98 and 101.22

minutes respectively. Zones D1 and D2 have loading points along the busy road J1 - J5, which would have had resulted in delays to enter loading point.

Among houses using bus (823 houses) about 53% of bus users are from five zones C3, D1, D2, E2 and F2 and the remaining percent of bus users are from the fourteen zones. Bus routes are also linked to public shelter locations, and hence the level of high bus usage in these zones will be useful for respective shelter planners as well. Zones having very high population (D2, F2) were the ones with highest demand for public shelters. Consolidated result analyses in conjunction with findings from individual models highlighted inter-relationship among ESFs. Table 7.3 presents the inter-relationships at a metric level. It can be observed that certain operational metric have forward and backward linkages with different ESFs.

Table 7.2 Zone-wise consolidated evacuation metrics from models developed in this thesis

Zone	Houses	Population	Warning time	Evacuation time	Clearance-time (cars)	Waiting-time (bus)	Means of Transport			Houses needing Shelter	Evacuees needing shelter
							Car	Bus	Pedestrian		
"A4"	162	797	15.17	90.73	29.98	6.23	113	23	26	19	96
"A5"	86	469	11.06	82.14	17.86	5.11	57	14	15	7	35
"B4"	167	860	11.75	80.98	25.17	12.15	127	22	18	17	77
"B5"	172	873	13.11	77.86	19.17	12.07	132	19	21	18	96
"B6"	195	1001	11.89	77.42	17.54	8.53	141	35	19	15	68
"C3"	340	1786	11.85	130.82	27.04	233.1	224	72	44	38	181
"C4"	82	400	13.95	83.79	17.52	19.29	52	12	18	12	49
"C5"	342	1633	12.58	84.81	19.41	10.89	236	56	50	33	143
"C6"	142	739	13.15	74.95	17.23	7.07	101	19	22	14	69
"C7"	283	1438	12.25	80.44	16.72	26.52	202	43	38	37	199
"D1"	719	3640	12.02	120.44	44.18	162.22	514	113	92	70	368
"D2"	377	1878	11.54	109.63	32.23	146.53	259	71	47	37	184
"D3"	192	965	10.59	84.41	27.05	16.92	129	37	26	16	77
"E2"	398	1994	12.38	103.98	32.06	81.3	255	81	62	45	229
"E8"	211	1043	12.78	87.54	16.05	53.29	148	30	33	13	71
"F2"	746	3650	12.8	101.22	29.79	98.67	526	103	117	69	350
"F3"	371	1778	12.16	87.33	25.85	22.65	272	53	46	38	200
"F8"	157	800	11.65	87.1	15.1	60.85	111	20	26	16	69

Table 7.3 Inter-relationship among ESFs explained using operational metrics

Operational metric	**Lead agency – Information provider**	**Downstream stakeholder - Recipient**	**Usefulness of the information**
Departure time curve (cumulative % departure vs time)	Warning and Informing group (ESF – 1)	Transport authorities (ESF-2)	To know the onset of evacuation vehicles at loading points at each zone.
Mode of transport (% car users)	Transport authorities (ESF-2)	Shelter Information management authority (ESF-3)	To manage parking space for car users and arrival patterns.
Travel time to shelter (cumulative % arrivals to shelter)	Transport authorities (ESF-2)	Shelter Information management authority (ESF-3)	To estimate arrival time profile of evacuee at shelters.
Public transport routes to shelters	Transport authorities (ESF-2)	Shelter Information management authority (ESF-3)	To manage evacuee registration process on arrival.
Zone-wise shelter location and demand	Shelter Information management authority (ESF-3)	Transport authorities (ESF-2)	One component of traffic volume estimation is to know the traffic movement to sinks/destination (shelters)
Vacant capacity in shelter (during evacuation)	Shelter Information management authority (ESF-3)	Transport authorities (ESF-2)	To send buses with evacuees only to vacant shelters.

ESF level preparedness – Generic tasks to be performed

An evacuation plan describes an ESF's role and response during emergency for a planned threat. An ESF plan is developed for an identified threat scenario and elaborates the organisational response in case of eventuality. Disaster impact scenarios are used to evaluate the ESF plan for various evacuation KPIs. Evacuation planning does not stop at preparing 'plan documents' at the ESF level. It also does not stop at making a compendium of ESF plans into another bigger plan. There is a need for an ESF to develop evidence-based understanding of their preparedness, uncertainties in household behaviour and ESF's 'inter-relationships with other ESFs' in terms of information exchanged and impact of other ESF's role on their plan. In this task, Table 7.3 provides an understanding of interrelationship at the operational metric level. Further to this understanding, a need for developing a system to enable collective response during a large-scale emergency is argued as very essential. Such a system has a role to facilitate inter-agency coordination, communication and decision making. Figure 7.1 presents the generic activities to be conducted by all the ESF organisations.

Figure 7.1 Evacuation planning cycle

The evacuation plan is implemented during an actual emergency by evacuation responder organisations collaboratively. Some of the organisational resources could be impacted during an emergency. For example, a major evacuation route might be blocked and hence inaccessible during emergency. Such an impacted organisation having reduced resources, needs to implement their plan and hence will influence the next phase responder's plan in the overall evacuation. After evacuation, any damaged capacity (e.g. highways) need to be re-built as capacity building initiatives. The learning from the actual response results in changes in evacuation plan and further behaviour research. Apart from practising the implementation of evacuation plan during exercises, model provides a platform for evaluation of evacuation plans and testing alternative strategies.

7.3 **An Integrated approach for evacuation planning**

One of the overarching objectives from the previous chapters (chapters 4 to 6) was to answer the research question *Q4: How OR-based approach can help GOs in evacuation planning?* By developing ESF-specific OR models, running scenario experiments and analysing results and sensitivity of parameters, each ESF developed 'model-based understanding' of preparedness by measuring its KPIs. Thus, each of the three models respectively supported evacuation planning of one support function. *However evacuation is a collective response of all the ESFs put together beyond their individual organisation preparedness.*

Three ESFs are phases that sequentially follow in timeline of evacuation and are hence inter-related. Some of the existing evacuation models (predominantly transportation models) focused on individual phases (e.g. OREMS). In the literature, impacts of one phase over the other were studied using sensitivity analyses in transportation models. However, the analyses in the Section 7.2 highlighted the linkages at an operational metric level. This is of high importance considering the finding that lack of multi-agency coordination is one of the major pitfalls found after Hurricane Katrina.

An integrated approach is defined in this thesis as "*an OR model-based multi-agency approach of evacuation planning, additional to single agency preparedness, that considers 'the inter-relationship/inter-connectedness of various evacuation support phases'* ". How can this integrated approach be implemented?

London Resilience Partnership comprises more than 170 organisations for ensuring/supporting London's preparedness to emergencies. A three-tiered Gold-Silver-Bronze 'Command and Control protocol' provides '*a strategic response of the partnership to a major emergency'* (Source: London Prepared website, 2012). The OR model-based approach advocated in this thesis will be of interest to the 'nodal EMA agency' (e.g. London Resilience Forum) for the planning evacuation response to identified threats. Lead agency of each ESF with an understanding of the inter-connectedness and inter-relationship could inform a need-based collaborative evacuation preparedness using OR models.

Though the primary driver for the integrated approach is 'interconnectedness and inter-relationships', there are various benefits by adopting an integrated approach. Household demographic data are common across the ESFs. Common collection by a single agency can reduce the overall collection cost by reducing redundancy in collection. This can also enable consistent data shared across the responders.

The integrated Evacuation Model (iEM) has three modules corresponding to three ESFs. Three modules of the iEM use two OR/MS techniques namely ABM and optimization developed in NetLogo and MS-Excel, respectively. These models were not integrated into a single model. Moreover, it could also be argued that the modules reflect different organisations responsible for specific response phase in an evacuation timeline, and hence partial integration (data sharing level) of models might reflect the 'module-organisation' relationship. For example, 'Transport for London' (TfL) is an umbrella organisation for managing the transport services of London metro. However, TfL's main focus is likely to be on the transportation module (ESF-2) and less on others. Hence, semi-integration of the modules could be argued as a possible advantage.

Understanding about the behaviour household during emergency is the foundation to the success of evacuation. This thesis does not claim to develop an improved understanding of household behaviour or preparedness and influencing the same for improved overall response. The thesis has implemented existing household behaviours into OR-based evacuation models and measured its sensitivity using evacuation KPIs.

The literature review and feedback interviews within the ERGO countries did not identify a comparable integrated product. Most of the models focus on one evacuation phase. At module level, there are much more sophisticated products. UMS is a full-fledged warning dissemination product with its forward integration with telecom service providers. OREMS and DynaMIT are widely used transportation software that have inbuilt features for modelling complex multi-lane road networks. This thesis argues that the provision of multi-agency planning through a common platform is a unique feature of iEM. This chapter used zone-wise model results as an evidence base for proposing multi-agency multi-phased integrated approach. The next chapter reviews the research questions addressed in this thesis, contribution and further scope for research.

CHAPTER EIGHT: DISCUSSION OF FINDINGS AND CONCLUSIONS

This chapter begins with the review of research questions and how these were addressed in this thesis. The next section presents the main theoretical contributions of the thesis to literature. The limitations and further scope of research are presented in the third section followed by implication of models to the practitioners. The fifth section summarises the conclusions of the thesis. The final section presents reflection on the PhD process.

8.1 **Review of research questions**

The research questions were presented in Chapter 1 of this thesis and the following paragraphs presents 'how the thesis has addressed each research question'.

Q1: What is the need for modelling ESFs?

This question has been addressed by identifying gaps using literature (Section 2.4). Summary of models and ERGO findings synthesised the existing models along ESFs (Section 2.8.3, 2.9.6, 2.10.3). Models have been used for 'evaluating' evacuation preparedness of ESFs using evacuation KPIs (Perry and Lindell 2003, Altay and Green 2006). However, 'the impact of the household behaviours identified in this thesis in each ESF' evacuation KPIs has not been investigated earlier. A model was needed to illustrate implementing the behaviours and study them. Various purposes of models (section 7.1) are 'testing and experimentation of evacuation plan alternatives, implementing response policies, simulation of worst-case scenarios, training, exercise and identifying bottlenecks and any scope for capacity development'.

Q2 and Q3: How do household evacuation behaviours impact different phases in evacuation?

The household behaviours and its uncertainties were identified using literature review. The identified behaviour and its impact at the EMA responses are presented below for each ESF. In ESF-1, based on literature review, household behaviour as warning informant to neighbours (Section 2.8.4) has been identified as a research gap in ESF-1. However, the uncertainties in informant behaviour such as defaulter percentage, time to begin, time to inform and neighbour selection policy were identified in this thesis and studied through sensitivity analyses in prototype model (Table 4.14) and in the ERGO city scale (Table 4.22a). ABM warning dissemination model provided platform for official and unofficial channels based warning dissemination. As there are various forms of failure of official channels (Table 4.18), failure categories were identified and model experiments were conducted and the impact on warning KPIs (warning level and notification time) was investigated.

In ESF-2, household's transport behaviours such as departure time and means of transport were identified as gap for investigation in this thesis (Section 2.9.7). However, the departure time is a function of when household receive the message (ESF 1) and then mobilisation time. A multi-modal ABM transportation model developed in this thesis provided platform for implementing evacuation road network, transport policies and household travel choice behaviour (Section 5.4.2). This model was used to study evacuation clearance times under various conditions.

- The impact of warning dissemination on departure time and hence evacuation time of the household has been studied using output of ESF 1 into ESF 2 (Section 5.5.1).
- Level of transport policy on controlling transient traffic represented as three categories {no, low, high} was sequentially studied to identify the impact of transient traffic level on ET (Section 5.5.2). This finding could inform the transient traffic control policy.
- Households choosing evacuation buses as their means of transport queue up in the nearest pickup point. There were four bus routes picking up evacuees from evacuated zone to shelters/destination. The dynamics of evacuation bus dispatching, household's waiting time for bus and ET for bus users were estimated using model experiment (Section 5.5.3). This finding could inform the bus dispatching policies.

In ESF 3, lack of household shelter choice-based holistic approach of shelter information management was identified as a gap in the literature review (2.10.3). The SIMS holistic approach provides a generalisable approach for shelter planning (Figure 6.1). The household shelter choices categorised as selfish choice, personal choice and allocated choice were identified in this thesis (Section 6.3.4). A household shelter choice was set and then a generic allocation model was executed repeatedly to study the impact on ET (Figures 6.9, 6.10, 6.11) and hopping behaviours (Figure 6.13).

Q4: How OR-based approach can help GOs in evacuation planning?

Literature review provided an understanding of state of the art OR models in each ESF Sections 2.8.3, 2.9.6 and 2.10.3. Literature review showed wide spread use of OR model for evacuation planning to test evacuation plans and measure evacuation performance during various scenarios. For the identified household behaviours (Q2 and Q3) in the three ESFs, this thesis has demonstrated ‘how respective ESFs can use OR models for evaluating preparedness using KPIs’. The models also helped in studying uncertainties in household behaviour parameters and its sensitivity.

Q5: How OR-based approach can provide an integrated evacuation planning environment?
Consolidated analyses of zone-wise evacuation performance (Table 7.2) and findings from ESF chapters indicated inter-linkages among ESFs and corroborate the need for multi-agency based planning. The developed model was used to show the inter-relationships and demonstrated the model’s use as planning environment using ERGO city. As the ABM and SIMS approach is customizable, these serve as a common platform across ESFs for integrated planning.

In summary, main household behaviour gaps for each ESF are lack of formal study of informant behaviour in warning dissemination, computing departure time for transportation model using warning time, uncertainty in means of transport, and uncertainty in shelter choice behaviour. The impacts of these behaviours have been studied using the model and are described in respective chapters (Chapters 4 to 6).

8.2 **Contributions of the thesis to literature**

This thesis has looked from the perspective of evacuation preparedness of supporting GOs. Evacuation is supported by different organisations in various evacuation phases, requiring separate organisation-level evacuation plans and hence a collective multi-agency response is needed.

Contributions on Warning Dissemination (ESF-1)

Warning system comprises ‘official channels’ (sirens, telephone, etc) and ‘unofficial channels’. The role of unofficial warning channel has been highlighted using empirical evidences of informing their neighbours (Parker and Handmer 1998, Sorensen 2000, Werrity et al. 2007, Hui et al. 2008). However, there are uncertainties in household’s warning informant behaviour such as 'whether they will inform their neighbours or not?', 'How many neighbours will they select to inform?', 'When will they depart the household?'. EMAs will be interested in measuring the warning dissemination effectiveness and the impact of unofficial channel. Hui et al. (2008) studied using ABM dissemination of warning between two communities based on trust. However, uncertainties in the ‘household informant behaviour’ have not been addressed in the literature, and this has been investigated in this thesis.

A prototype warning dissemination model of a hypothetical community of 1000 households was developed in ABM. Household uncertainties such as defaulter percentage, assimilation time and ‘time to inform’ were investigated through simulation experiments. It was found that even at a low level of informant behaviour, there was considerable increase in the overall warning levels in the hypothetical model. Implementation of household’s warning informant behaviour is a contribution of this thesis to the literature.

Detailed investigation of warning dissemination and particularly the uncertainties in unofficial warning channel in the prototype and ERGO city models provided a greater understanding of unofficial channel and warning dissemination KPIs. The model also provides a framework for further investigation. Better estimation of household’s warning time and informant behaviour enables more accurate estimation of departure time at the household level, which is a key in ESF-2.

Contributions on Evacuee Transport Management (ESF-2)

The use of custom-built models for evacuation transportation planning was found during the ERGO interviews. There is widespread use of OR/MS in the transportation phases (Santos and Aguirre 2004), using techniques such as optimization (Bretschneider and Kimms 2011, Pel et al. 2011, Ben-Akiva et al. 2012), ABM (Lansdowne et al. 2006, Dawson et al. 2011, Mas et al. 2012a,). However, the linkage with the warning dissemination data particularly the unofficial channels has not been studied and this thesis illustrated the potential for integrating the warning dissemination model with the transport management, factoring the behaviour of evacuees. This thesis studied the impact of warning dissemination on ET with/without unofficial warning behaviour.

The role of OR/MS models in managing evacuation buses has been studied in Margulis et al. 2006. However, means of transport choice is made at individual household, and with variability in the warning received time, when a household reaches its nearest pickup point is uncertain. This thesis has studied the arrival patterns at the destination using buses and developed ‘bus evacuation response curves’ using model results. Evaluation of controlling transient traffic management as a policy and their implication on KPIs was illustrated in this thesis.

Contributions on Shelter Management (ESF-3)

Optimization-based location-allocation models have been used for managing shelter demand and capacity (Sherali et al. 1991, Kongsomsaksakul et al. 2005, Ng et al. 2010). Historical data (Mileti et al. 1996, Brodie et al. 2006) and stated preference surveys (FEMA 2010) helped in understanding household sheltering behaviours. SIMS holistic approach synthesised the existing knowledge on emergency accommodation planning into series of steps to allocate shelters. A generic optimisation model for allocation of shelters was developed. Zone-wise analyses helped in understanding the distributiveness of shelter demand and allocating the available shelters during response. Mas et al. (2012b) noted that shelter choices are not always to the nearest. Even though EMAs provide shelter allocation advice, there were many household shelter choice behaviours categorised in this thesis and studied for its uncertainty.

Contributions to Evacuation Planning

Findings from the ERGO interviews indicated diverse use of models for evacuation planning. Synthesis of the evacuation models is a contribution to the OR/MS literature on evacuation modelling. This thesis has developed models using two different techniques namely 'Agent-based modelling and optimization' for three ESFs. As ABM is suitable for implementing behaviours at household level and 'optimization' to find the best strategy at system level, 'mixing these two techniques in different ESF models to harness advantages' is a contribution to OR/MS literature. Identifying the inter-relationships between ESFs at an operational metric level helped in highlighting the need for multi agency-based planning beyond individual ESFs.

The role of OR/MS models for more than one ESF has been found in the existing literature (Rogers and Sorensen 1991, Southworth 1991, Lammel et al. 2008, Taubenbock et al. 2009, Dawson et al. 2011, Mas et al. 2012a). The model developed in this thesis helped in studying the interconnectedness of the GOs, their individual evacuation policies, and studying its cascading effects. Instead of restricting preparedness at individual phases, this thesis has identified the need for integrated approach, and the role of model as a platform for integration.

8.3 **Further scope of research**

Evacuation timeline begins with making a decision to evacuate based on forecasted information or disaster impact. Making a preventive evacuation decision is complex with uncertainty of impact levels, cost, time available before strike and available alternatives. Evacuation decision making (Model 3) is a key component of preparedness framework (Figure 1.2) and argued to be beyond the scope of this work. The readers are directed to a thesis on evacuation decision making Kailiponi (2012). Model 1 of the ERGO framework investigates on 'How the public can be prepared by GOs for evacuation?' The readers are directed to Shaw et al. (2011a).

Model 1 and Model 3 will inform evacuation plans, and the thesis provides a model-based approach for understanding the household behaviours 'after an evacuation decision'. As this thesis covers only the three phases of evacuation (warning, transportation and sheltering), there is no conflict of interest and contribution with other two researchers in the ERGO project. Further, there are vital information related to the phases prior to warning (e.g. evacuation decision making, disaster impact), and post sheltering (e.g. relief logistics to support shelter operation) are excluded to be beyond the scope of this thesis and readers could refer to Altay and Green (2006) and Caunhye et al. (2012)

There are various planning assumptions about the evacuees that form the basis of evacuation plans. At times, the GOs hold some beliefs about the evacuee behaviour choices implicitly through their experience. Household behaviours are influenced by existing laws (e.g. cannot evacuate using cars), policies (e.g. no public transport support) and household preferences. These uncertainties in the behaviour of individual evacuating household can have impact on the overall evacuation KPIs. This thesis has demonstrated the use of OR evacuation models to implement and study the household behaviour uncertainties.

Apart from the conventional official channels, ERGO findings have highlighted the use of technology-based sophisticated warning channels as well as community-based warning dissemination. The potential for the existing social network as 'unofficial channel' can be harnessed further. A simulation model that can be used to test warning dissemination for various planning scenarios was presented. This thesis contributed to implementing and studying the uncertainty of unofficial channel behaviour.

ERGO city has been used as an illustration for developing models for three ESFs and also illustrating the need for integrated approach. The data used are simplified for illustration. For example, transportation model has only single-lane traffic with normal driving behaviour without any accidents, change in plans, etc. The simplicity of ERGO city limits the generalisation of findings to an actual city. However, the approach taken to model the three phases are valid and argued to be generalisable.

This thesis has illustrated OR-based integrated approach for large-scale evacuation planning using ERGO city case study. This thesis advocates a multi agency-based integrated approach using OR/MS models rather than restricting to individual ESF preparedness as a better preparedness strategy.

There are phases of evacuation beyond the three ESFs covered in this thesis like disaster relief logistics, making evacuation decision and modelling disaster impact, and the role of ORMS models with household behaviours can prove to be a useful toolkit.

The innovative application of model to generate awareness with the public was one of the findings in ERGO interviews and has practical implications. EMAs could explore the possibility of using visually appealing models to sensitise general public and raise the preparedness level. Generating awareness with the public would involve using the OR model as an exhibit in exercises or science exhibition centres to explain ‘How will the propagation of disaster be for a forecasted scenario’ and persuade them on evacuation preparedness. In summary, a ‘visually appealing model’ combined with ‘localised actionable information’ presented by subject matter experts to the public has a potential to influence their threat perception.

8.4 **Model implications to Emergency Management Practice**

Readers need to remember here that the EMAs respond to the life-threatening mass evacuation situation by their rich experience including gut feeling and intuition, backed by preparedness. The role of models in supporting preparedness has been elaborated with ERGO city case study.

- The analytical models in this context as a tool in the toolkit of EMAs are considered to be helpful by supporting the response plan with identified performance metrics, evaluate the implications of the planning assumptions, testing and choosing relatively better response option, support during training and exercise of evacuation preparedness.
- Simulated exercises are generally conducted for multi-agencies to test and exercise their evacuation plan collectively. The ABMs and SIMS models can be used as a platform to conduct multi-agency exercise for strengthening preparedness.
- Good understanding of the model features, the purpose and limitation of the model can evade over-reliance on the model results and encourage harnessing its strength for the intended use. The interpretation of the model results to actionable decision, making the evacuation decision and the implication of the decision made remain in the hands of the experienced EMAs. This entails a need for understanding 'how validation was done in this thesis?', which was presented in Table 3.2.

8.5 **Thesis conclusion**

ABM provides a suitable OR/MS modelling framework for household evacuation behaviours in three ESFs. ABM and SIMS demonstrated in this thesis can support ESF preparedness to incorporate household behaviours. This thesis does not recommend replacement of individual organisation-level preparedness, which is essential. Instead the thesis advocates using OR model-based integrated approach to further strengthening preparedness and 'inter-agency coordination'.

8.6 **Reflection on the PhD process**

I was working as a research assistant in the ERGO project from May 2008 till the end of project, and was also doing my PhD. The initial stage of contacting countries to sign up for 'ERGO case study' was a very intensive period and a new experience to me. Organising data collection visits to 10 countries and to encourage as many expert interviews in each were challenging. The semi-structured interviews, presentations and reports received from the countries served as an important data source for the models.

In parallel, the three models were being developed. Close to four hours of model presentation to the ERGO project's Advisory Board members provided detailed evaluation of the modelling approach and defining the scope of the models. Preparing country-wise feedback presentations, master class and receiving feedback on the model demonstrations from the practitioners were invaluable for thesis quality. Overall, the experience in the ERGO project has been very enriching and also was a great support for my PhD and career aspirations.

The ‘Research Methods Course’ (RMC) provided the foundation for pursuing PhD. The dedicated teaching effort shown by faculty members in lectures was inspiring. Feedbacks from the qualifying report and the viva exam provided an opportunity to improve the PhD. Apart from RMC in the university, I attended skill development courses in NATCOR (National Taught Course in Operational Research) and research methods workshop in Cambridge, and these were useful.

ESRC seminar conducted in Aston Business School with ‘academics and practitioners’ provided critical review on the warning dissemination model presentation. Another presentation in the ESRC seminar held in Cranfield University campus was helpful to receive critical comments from academics during presentation. All the three models were presented during that seminar. This seminar helped in organising a one-to-one model peer review with an experienced researcher. Apart from these, presentations in conferences such as ICEM and InterCEPT provided an opportunity for receiving feedback on the models.

The experience of writing ERGO project report, a conference paper in POMS and ICEM, a journal article in ‘Procedia Engineering’ and an article in ‘European Journal of Operational Research’ on the PhD models was very rewarding. Preparation of manuscript for the papers and critical feedbacks by Dr. Pavel Albores and Prof. Duncan Shaw was a learning experience for improving my writing skills.

Reflection on PhD experience

My most enjoyable moments were when the idea of household behaviour and modelling it was taking shape. I owe a lot to the discussions with Dr. Pavel Albores and Prof. Duncan Shaw for shaping the ideas. I enjoyed coding and implementing these behaviours into models. Nothing else existed except the model and the code. Those were my most productive days.

I was unemployed for over 1.5 years during PhD. During that period, focusing on thesis and making progress was an arduous challenge. Ironically, this was the period of highest expense, with challenges from other fronts when I could not afford to continue. Having good financial plans and support during PhD can make the duration short, less stressful and more rewarding.

I feel that social support and networking are important for a researcher particularly during the PhD period. Though I tried changing myself on couple of instances, I remained socially isolated. I do not know how to, but would encourage other PhD aspirants to seek and give support to fellow researchers and enjoy the PhD process.

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APPENDIX – A

Table A.1 Evacuation zone details (File: evacuation-zone-coordinates-file.prn)

Sl.No	**Variable**	**Description**
1	Zone-ID	Zone code
2	X-Cor	Lower X-Coordinate
3	Y-Cor	Lower Y-Coordinate
4	X-Cor	Upper X-Coordinate
5	Y-Cor	Upper Y-Coordinate
6	Pickup List	List of bus pickup points for the zone

Table A.2 Household warning response details (File: household-warning-time-file.prn)

Sl.No	**Variable**	**Description**
1	Sl.No	Serial Number
2	House-id	Agent-ID from Warning dissemination model
3	X-cor	X-coordinate of the house
4	Y-Cor	Y-coordinate of the house
5	Zone-ID	Zone code
6	Recd-Msg	Whether the household received the warning message?
7	Recd-time	At what time the household received first warning?
8	Depart-time	Time of departure from the house
9	Evac-or-not	Whether the household will evacuate?
10	Family-size	What is the size of the family?
11	Means-of-transport	Whether means house will use to evacuate? {CAR, BUS, PEDESTRIAN}
12	Need-Shelter	Whether the house will require public shelter?

Table A.3 Road Network connectivity (File: road-network-connectivity-file.prn)

Sl.No	**Variable**	**Description**
1	Sl.No	Serial Number
2	Junc-ID	ID of the Junction (e.g. J12)
3	Junc-Xcor	X-coordinate of the junction
4	Junc-Ycor	Y-coordinate of the junction
5	Outward Connectivity	If it is a junction, specify the array list of outward junctions. Otherwise FALSE

Table A.4 Traffic signal details (File: traffic-signal-details-file.prn)

Sl.No	Variable	Description
1	Junc-ID	ID of the Junction ahead.
2	Order-Of-Signal	A sequence number for the signal within the same junction
3	X-Cor	Starting point (Xcor) of signal visibility zone.
4	Y-Cor	Starting point (Ycor) of signal visibility zone.
5	X-Cor	Ending point (Xcor) of signal visibility zone
6	Y-Cor	Ending point (Ycor) of signal visibility zone

Table A.5 Evacuation route to Exit points (File: evacuation-route-to-exits.prn)

Sl.No	Variable	Description
1	Zone-ID	Zone code
2	Origin	Origin - Loading point Junction
3	Destination	Destination - Exit point
4	Route	Route Plan

Table A.6 Evacuation route to Shelters (File: evacuation-route-to-shelters.prn)

Sl.No	Variable	Description
1	Zone-ID	Zone code
2	Shelter-ID	ID of the shelter
3	Origin	Route plan to shelter - Origin
4	Destination	Route plan to shelter - Destination

Table A.7 Loading points for each junction (File: evacuation-route-loading-points.prn)

Sl.No	Variable	Description
1	Junc-ID	Junction ID
2	X-Cor	X-Coordinate of the loading point
3	Y-Cor	Y-Coordinate of the loading point
4	Heading	Heading at the loading point

Table A.8 Evacuation Bus routes (File: bus-route-file.prn)

Sl.No	Variable	Description
1	Bus-Route	Bus route ID
2	Origin	Origin of the bus
3	Destination	Destination/Final stop of the bus
4	Route-plan	Evacuation bus route.

Table A.9 Transient vehicle routes (File: transient-vehicle-routes-file.prn)

Sl.No	Variable	Description
1	Route-Code	Transient vehicle route name
2	Origin	Origin of the transient vehicle route
3	Destination	Exit point of the transient vehicle route
4	Route plan	Transient vehicle route plan

Table A.10 Shelter coordinates file (File: shelter-coordinates-file.prn)

Sl.No	Variable	Description
1	Shelter-ID	Unique ID for the shelter
2	X-Cor	X-coordinate of the shelter
3	Y-Cor	Y-coordinate of the shelter
4	Nearest destination	Exit point nearest to the shelter

APPENDIX – B

Table B.1 Trip-Sheet from the model for Route – 1

Trip-Sheet Sl.No	Bus-ID	Departure-time	Arrival at destination	Clearance time	Evacuees transported	Houses Evacuated	Vacant seats
1	5168	30	61.16	31.16	31	5	29
4	5695	40.08	70.76	30.68	27	6	33
7	6936	50.04	79.66	29.62	55	9	5
10	7625	60	88.68	28.68	58	10	2
14	8161	70	97.62	27.62	57	12	3
15	8453	80	100.98	20.98	32	6	28
22	8627	90	113.68	23.68	21	3	39
26	8661	100	125.26	25.26	1	1	59
31	8709	110	140.34	30.34	0	0	60
37	8744	120	146.36	26.36	0	0	60
42	8798	130	161.68	31.68	0	0	60
48	8809	140	173.84	33.84	0	0	60
49	8814	150	173.88	23.88	0	0	60
55	8818	160	192.24	32.24	0	0	60
60	8822	170	204.22	34.22	0	0	60
61	8826	180	204.26	24.26	0	0	60
68	8830	190	222.8	32.8	0	0	60
69	8834	200	222.84	22.84	0	0	60
72	8838	210	232.06	22.06	0	0	60
77	8842	220	246.76	26.76	0	0	60
79	8846	230	249.64	19.64	0	0	60
85	8850	240	268.02	28.02	0	0	60
87	8854	250	274	24	0	0	60
90	8858	260	280.78	20.78	0	0	60
98	8862	270	304.44	34.44	0	0	60
100	8866	280	307.52	27.52	0	0	60
105	8870	290	319.7	29.7	0	0	60
109	8874	300	328.8	28.8	0	0	60
114	8878	310	334.84	24.84	0	0	60
116	8882	320	343.92	23.92	0	0	60

Table B.2 Trip-Sheet from the model for Route – 2

Trip-Sheet Sl.No	Bus-ID	Departure-time	Arrival at destination	Clearance time	Evacuees transported	Houses Evacuated	Vacant seats
2	5169	30	65.62	35.62	59	15	1
6	5681	40	74.52	34.52	58	12	2
9	6931	50	82.08	32.08	60	12	0
13	7626	60	93.76	33.76	59	12	1
17	8162	70	104.18	34.18	60	11	0
20	8458	80.1	110.76	30.66	59	11	1
21	8628	90	113.54	23.54	60	13	0
28	8662	100	129.78	29.78	60	16	0
29	8710	110	138.16	28.16	57	12	3
38	8745	120	147.2	27.2	60	11	0
44	8800	130.04	165.7	35.66	59	11	1
45	8810	140	165.76	25.76	57	12	3
50	8815	150	175.8	25.8	58	12	2
54	8819	160	191.92	31.92	60	12	0
56	8823	170	195.42	25.42	60	12	0
59	8827	180	202.7	22.7	56	11	4
67	8831	190	221.76	31.76	59	12	1
71	8835	200	231.18	31.18	59	13	1
76	8839	210	244.86	34.86	56	12	4
78	8843	220	249.18	29.18	58	14	2
81	8847	230	255.92	25.92	56	11	4
86	8851	240	270.38	30.38	60	12	0
89	8855	250	278.92	28.92	57	13	3
93	8859	260	283.26	23.26	60	11	0
96	8863	270	295.06	25.06	0	0	60
103	8867	280	315.48	35.48	0	0	60
104	8871	290	315.54	25.54	0	0	60
112	8875	300	330.52	30.52	0	0	60
117	8879	310	343.96	33.96	0	0	60
118	8883	320	348.78	28.78	0	0	60

Table B.3 Trip-Sheet from the model for Route – 3

Trip-Sheet Sl.No	Bus-ID	Departure-time	Arrival at destination	Clearance time	Evacuees transported	Houses Evacuated	Vacant seats
5	5170	30	72.4	42.4	48	11	12
11	5682	40	89.72	49.72	59	11	1
19	6932	50	107.16	57.16	57	13	3
23	7627	60	116.96	56.96	59	10	1
27	8163	70	129.7	59.7	60	13	0
30	8454	80	138.76	58.76	60	12	0
34	8629	90	141.86	51.86	58	13	2
35	8663	100.02	143.94	43.92	60	13	0
36	8711	110	146.06	36.06	59	12	1
39	8746	120	150.56	30.56	56	11	4
43	8799	130	163.64	33.64	60	15	0
46	8811	140	168.46	28.46	57	12	3
52	8816	150	184.4	34.4	58	13	2
53	8820	160	191.46	31.46	57	10	3
58	8824	170	197.5	27.5	60	13	0
62	8828	180	207.36	27.36	57	12	3
64	8832	190	216.66	26.66	58	11	2
73	8836	200	234.06	34.06	59	13	1
74	8840	210	236.34	26.34	59	13	1
82	8844	220	256.38	36.38	59	9	1
84	8848	230	263.98	33.98	58	10	2
88	8852	240	274.28	34.28	60	11	0
94	8856	250	284.98	34.98	58	10	2
95	8860	260	285.9	25.9	55	12	5
99	8864	270	305	35	57	13	3
101	8868	280	310.34	30.34	59	11	1
108	8872	290	321	31	59	13	1
111	8876	300	329.76	29.76	59	12	1
113	8880	310	334.36	24.36	55	10	5
119	8884	320	348.9	28.9	48	8	12