Practical and Conceptual Issues in the Use of Agent-based Modelling for Disaster Management

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Abstract

Application of agent-based modelling technology (ABM) to disaster management has to date been limited in nature. Existing research has concentrated on extending the model structures and agent architectures of complex algorithms to test robustness and extensibility of this simulation approach. Less attention has been brought to bear on testing the current state-of-the-art in ABM for modelling real-life systems.

This thesis aims to take first steps in remedying this gap. It focuses on identifying the practical and conceptual issues which preclude wider utilisation of ABM in disaster management. It identifies that insufficient attention is put on incorporating real-life information and domain knowledge into model definitions. This research first proposes a methodology by which some of these issues may be overcome, and consequently tests and evaluates it through implementation of InSiM (*In*cident *Si*mulation *M*odel), which depicts reaction of pedestrians to a CBRN (chemical, biological, radiological or nuclear) explosion in a city centre.

A number of steps are conducted to obtain real-life information related to human response to CBRN incidents. This information is then used for design and parameterisation of InSiM which is implemented in three configurations. In order to identify the effects use of real-life data have on the simulation results each configuration incorporates the information at different level of complexity. The effects are assessed by comparison of the generated dispersion patterns of agents along the city centre. However, use of conventional statistical goodness-of-fit tests for assessing the degree of the difference was challenged by inhomogeneous nature of the data. Hence, alternative approaches are also adopted so that results can be qualitatively assessed. Nevertheless, the evaluation reveals significant differences at global and local level.

This research highlights that incorporation of real-life information and domain knowledge into ABM is not without problems. Each time a problem was addressed, additional issues began to emerge. Most of these challenges were related to generalisation of the complex real-life systems that the model represents. Therefore, further investigations are needed at every methodological step before ABM can fully realise its potential to support disaster management.

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Chapter 1

Introduction

1.1 Motivation

There have been many large-scale disasters with personal, organisational, and societal impacts in the last decade. Therefore, disaster management, which focuses on taking the necessary steps towards providing civil protection (MacFarlane, 2005), has become a key social and political concern. As a consequence a number of research projects have been undertaken to provide expertise and technologies that can help to mitigate the consequences of these events or to better prepare for the future.

One of the technologies whose potential is being explored is agent-based modelling (ABM). The increased interest is shown, for example, by holding a special workshop (Agent Technology for Disaster Management; Jennings et al., 2006) within the International Conference on Autonomous Agent and Multi-agent Systems in 2006 to investigate the applicability of ABM to support processes related to incident mitigation, preparedness, response and recovery. In particular, it has been demonstrated that ABM can be applied to facilitate data acquisition (e.g. search for victims in debris from collapsed buildings; Nourbakhsh et al., 2005), information production (e.g. prediction of tube passenger movement in emergency situations; Castle, 2007), decision support (e.g. integration of real-time updates from the incident site to the simulated scenario; Kleiner et al., 2006) and action coordination (e.g. task prioritisation during a response to large building fires; Wagner et al., 2003).

The primary advantage of ABM is related to its capabilities of depicting the dynamics of the modelled system through interaction of the entities from which that system is formed (de Smith et al., 2007; Goodchild, 2005; Maguire, 2005). These entities are represented as agents (independent software programs) that are capable of making autonomous decisions on how to react to different situations. This bottom-up approach is one of the main reasons why this simulation technology has become very attractive for modelling complex and dynamic real-life systems (O'Sullivan and Haklay, 2000).

Although the above shows strong benefits in using ABM as a standard tool for disaster management policy planners and first responders, there is only very limited reporting of its active use on the same level as, for example, GIS systems or LBS applications. This thesis is looking at identifying the basis for the lack of interest in utilising this emerging technology as an alternative tool for generating disaster related information for decision making.

1.2 Research Aim and Objectives

The work presented in this thesis focuses on bridging the gap between research and utilisation of ABM for solving real-life problems related to the mitigation and response to large-scale incidents. The overall aim of this research is to advance the state-of-the-art of agent-based simulation to produce richer models that can realistically represent real-life disaster management systems. This is done by identifying and consequently addressing some of the issues and problems that preclude its wider utilisation within this application domain. To achieve this aim the following research objectives are formulated:

Objective 1: Review and critically discuss current state-of-the-art agent-based modelling in disaster management with respect to its suitability for simulating real-life domain specific systems.

Objective 2: Identify problems and issues that are connected with the development of such models and summarise them in a transparent form.

Objective 3: Propose an advanced methodology for the development of domain specific agent-based models which focus on addressing the identified problems and issues.

Objective 4: Test and evaluate the methodology by developing an agent-based model through following each of its suggested steps.

Objective 5: Analyse outcomes and findings from objectives 1-4 and make appropriate recommendations in the form of directions for future research.

1.3 Scope of the Research

Disaster management is a very complex domain comprising of numerous, diverse systems connected together in an integrated emergency management (IEM) framework around which involved organisations co-ordinate and link their activities (Cova, 2005). Even though incident, emergency, and disaster are by some viewed as three different acts (e.g. Quarantelli, 1954 uses this order to hierarchically categorise the events based on the extent of their impact) in this thesis they are considered as synonyms under a single definition provided in the Civil Contingencies Act (The Act; Great Britain, 2005). The Act defines an emergency as an event that "*threatens serious damage to human welfare, environment, or security of the United Kingdom*".

Due to such a general definition of scope and because of the extensive number of organisations and processes that are involved in disaster management it was found necessary to introduce constraints delimiting the focus of this research.

Therefore, close co-operation with two experienced incident commanders from Nottinghamshire Fire and Rescue Service was established from the beginning of this project to determine in what areas additional research is needed. During the initial discussions it was highlighted that threats of chemical, biological, radiological or nuclear (CBRN) incidents have been given special attention in the post 9/11 era.

This type of incident involves the deliberate release of dangerous material into an area with high concentrations of people such as the centres of large cities, or locations of high profile events (Home Office, 2004). Such an incident is intended to cause maximum damage in terms of fatalities and/or downstream economic and political consequences. Since CBRN incidents are connected with the spread of contaminated material, they challenge existing frameworks of local response which have not been developed to acknowledge this specific type of emergency. Hence, it was decided to concentrate this research towards emergency response to a large urban CBRN incident to explore the potential of ABM in specifying improvements to the response procedures.

The first thing incident commanders, who are responsible for managing the response operation, have to do is to delineate the affected area into inner and outer cordon zones to stop the contaminant from spreading into the neighbourhood and to provide necessary space for placement of the on site facilities for the response teams (HM Government, 2005b). Therefore, the successfulness of the search and rescue operation is highly dependent on the correctness and efficiency with which the cordon zones are setup.

The highly dynamic nature of the CBRN incident requires rapid decisions regarding the actual locations of the cordon zones. Hence, all necessary information that can support such decisions must be available. In this instance ABM can be a valuable asset since it could provide information regarding the temporal emergence of the complex system that combines together people, decisions and processes related to the management of the CBRN cordons. Therefore, the focus of this research is further narrowed down to utilisation of ABM as an alternative source of information to support decisions related to identifying the most appropriate locations of the CBRN cordon zones.

The analysis of the response to 7th July 2005 London bombings revealed that current procedures tend to focus too much on the response processes and requirements of the emergency services rather than on needs and priorities of the people involved (London Assembly, 2006). Consequently, this research concentrates on highlighting the importance of understanding the behaviour of affected people and considering such information during the decision making process by which the locations of the cordon zones are determined. In particular, it attempts to identify whether ABM can be used to determine dispersion patterns of affected people around the incident area by simulating the human response to such events.

Since human behaviour is inherently spatial, it is important to consider geographic information in both (i) representation of the real-life environment in the simulation model and (ii) definition of the agent's interactions. Hence, this thesis pays special attention to spatial aspects of human behaviour and its representation within the simulation models.

1.4 Structure of the Thesis

A brief summary of the remaining ten chapters is provided in the following paragraphs.

Chapter 2: Literature Review

Chapter 2 provides a definition of ABM and highlights the challenges such technology faces when applied to the simulation of complex social systems. This chapter further contains an extensive description of the state-of-the-art in ABM in disaster management. A number of existing models, which simulate diverse systems of disaster management, are reviewed from several different perspectives to identify important gaps in current research. The models are evaluated through diverse criteria that are defined with consideration of both the AI and disaster management domains. This chapter concludes with a set of research questions.

Chapter 3: Methodology

Chapter 3 commences with an overall research question that narrows down the research focus based on the findings of the literature review. It was identified that in the current disaster management related ABM research, consideration of real-life information during the model development process has been paid to only limited attention. With respect to this issue a methodology is proposed which aims to bridge this gap. Due to the diversity of situations that can be represented by ABM, it was found necessary to keep the methodological steps defined at an appropriate level of abstraction. However, to test the suitability of this approach it is further expanded of specific methods and techniques which are proposed for development of a test model InSiM (*In*cident *Si*mulation *M*odel) which simulates the situation in a city centre directly after an explosion of a CBRN bomb. Each step of the methodology, together with the outcomes of its application, are discussed in Chapters 4 - 9.

Chapter 4: Understanding the Application Domain

This chapter concentrates on gaining further insight into the application domain to identify what problems and issues response to CBRN incidents currently faces. To observe the system from the perspective of the response personnel two incident commanders from Nottinghamshire Fire and Rescue Service actively participated during the analysis conducted in this chapter. The findings of this analysis provide a rationale for the development of a use case scenario and the selection of an appropriate perspective from which the system can be observed and simulated.

Chapter 5: Experimental Data Collection

Chapter 5 describes the process that is used for the collection of data regarding the human reaction to a CBRN explosion. In order to reduce biases caused by limitations of a single technique two methods are defined to obtain independent views on the situation. Due to the lack of historical data of the required level of detail or quality, the selected techniques are of a qualitative nature. This enables the development of an unrestricted view on the response behaviour. As well as collecting information on human reactions to such events the studies also concentrate on identifying what factors influence such behaviour.

Chapter 6: Analysis of Experimental Data

In this chapter the data collected by the methods described in previous chapter are processed. Due to the qualitative nature of the data and the small size of the interviewed population sample an emphasis is put on qualitative analysis to identify what effect a CBRN explosion has on people's behaviour. Nevertheless, the findings are further quantified to fulfill the requirements of its use in the following methodological steps. In order to determine whether demographic background plays an important role in human reaction the data are analysed with respect to the participants' sex, age and the location in which the experiment took place.

Chapter 7: Development of the Geo-simulation Model

Chapter 7 discusses the development of a conceptual model which represents the key processes and essential characteristics that are further implemented in InSiM. The definition of the conceptual model draws upon findings from the analysis of the experimental data presented in the previous chapter. This is done by specifying and justifying limitations and constraints by which the complexity of the real-life system is reduced. The conceptual model consists of three building blocks: (i) definition of simulation space that represents the real-life environment, (ii) agent specification which describes the main characteristics, behaviours, and interactions of the agents, and (iii) general model characteristics that depict the key model components related to its operation.

Chapter 8: Model Implementation & Case Studies

This chapter outlines the structure of InSiM in a more formal way. The model's key components are defined according to the conceptual model presented in the previous chapter. In order to determine the importance of utilisation of real-life information when defining behaviour of the interacting agents, InSiM is developed in three configurations. Each configuration incorporates the information at a different level of complexity. In addition, this chapter also includes a definition of the case studies that are used as test scenarios for running InSiM. The scenarios are specified with consideration of the needs of the incident commanders to generate information that could support decision making during preparation of a response to CBRN incidents.

Chapter 9: Analysis of Results & Model Evaluation

Chapter 9 presents techniques that are tested for analysis of the data obtained by running InSiM on the defined use case scenarios. The aim of the analysis is to identify to what extent outputs generated by the three InSiM configurations differ with respect to the dispersion patterns of agents on the simulation space at the end of the designated time period. This is done by applying analytical techniques and goodness-of-fit tests that are capable of detecting differences between the agent distributions. In addition, the selected techniques are evaluated with respect to their effectiveness and accuracy with which they can answer the questions asked on the simulation model. The second part of this chapter concentrates on the evaluation of InSiM functionality through validation, verification and calibration.

Chapter 10: Discussion

This chapter discusses the benefits and shortcomings of the applied techniques and reexamines the methodology proposed in Chapter 3. The discussion is organised into three sections, each concentrating on analysing the research from a different perspective. Firstly, the impact of the identified practical and conceptual issues on the research project is highlighted and approaches by which the issues are addressed are discussed. Secondly, the methodology is evaluated through the same set of questions by which competence and integrity of existing agent-based models for disaster management have been assessed in Chapter 2. Finally, the last section concentrates on discussing the usability of InSiM within the context of disaster management.

Chapter 11: Conclusions & Further Research

Chapter 11 presents a summary of the research findings with respect to the proposed research aim and objectives. It also highlights contributions of this research to the scientific community. This thesis concludes with a set of recommendations for further research.

Chapter 2

Literature review

2.1 Introduction

The purpose of this chapter is to gain an understanding of the state-of-the-art in applying ABM to disaster management. It focuses on detecting problems and issues developers face when implementing models related to this real-life domain. Special attention is given to identifying how these problems have been addressed and whether the selected approach has been successful. The aim of the literature review is to identify gaps in the current research and provide motivation and focus for the work presented in the subsequent chapters.

In order to identify how successful applications of ABM into disaster management have been to date, 35 geo-simulation models developed in last two decades were assessed from several perspectives. This is not meant to be a complete list, the models were selected with the intention of including diverse applications developed by researchers from three different scientific disciplines. Approximately 50 % of the papers were published by computer scientists and knowledge engineers. The remainder are almost equally distributed between sociology, psychology, and geospatial science research.

An apparent pattern can be observed regarding the focus of the publications. The fundamental paradigms and concepts of the ABM technology were predominantly published in peer-reviewed scientific journals. The majority of the case studies were published in conference proceedings. The popularity of the conference presentations might lay in its faster review process in comparison to a journal which can take several months. The simulation models, by that time, usually become out of date or have overcome major structural changes due to the popular rapid prototyping software development process. However, the preference in conferences also poses questions with respect to the quality and reliability of the developed models. This indicates a preference in exploring the technique capabilities by developing prototypes rather than robust and intelligent software programs demonstrating scientific potential of this simulation approach.

The remainder of this chapter is organised into three main sections. In Section 2.2 a definition of ABM is provided and its benefits and limitations related to simulation of processes in complex social systems are highlighted. Since social systems are embedded in geographical space the importance of incorporation of spatial considerations into the simulation models is discussed. This section concludes with identification of (i) the purposes for which recent models were developed and (ii) disaster management systems which they represent. The consequent Section 2.3 concentrates on reviewing recently proposed model development processes. Special attention is given to discussing considerations and challenges that have been identified in recent peer-reviewed publications. The findings are organised into a set of aspect categories. With respect to these categories an extensive list of questions is proposed by which the 35 publications are further evaluated. The final section of this chapter (Section 2.4) summarises the issues and problems that have been identified during analysis of the scientific literature and proposes a set of research questions.

2.2 Agent-Based Models in Disaster Management

In this section the definition of ABM as it is understood within this thesis is provided (Section 2.2.1). The challenges and problems that are connected with models representing complex social systems are discussed in Section 2.2.2. Section 2.2.3 evaluates relevance of purposes for which the models were developed with respect to the needs of the disaster management.

2.2.1 Agent-based Modelling

In the last decade ABM have been adopted by many researchers as an alternative approach to simulation of processes in complex systems. The fact that this technique is capable of representing the characteristics and movement of the entities from which the system is formed without relying purely on mathematics is seen as one of its main advantages (Longley and Batty, 2003). The behaviour is in this instance defined by a set of rules e.g. *When reaching a crossroad, turn left*. Cavezzali and Rabino (2003) argue that this is a more realistic way since not all complex human interactions can be expressed as mathematical equations. Due to this simulation approach flexibility and wide applicability no universal definition of an agent exists. Nevertheless from the modelling perspective, there are several characteristics which are common for most agents (Maes, 1994; Wooldridge and Jennings, 1995 further extended by Epstein, 1999; Benenson and Torrens, 2004):

- **Autonomy:** Each agent is a self-organised unit that can make decisions without having its behaviour restricted, or governed by a centralised control. The behaviour is therefore dependent purely on agents' internal characteristics and the information they obtain by interaction with others or the environment.
- **Heterogeneity:** The heterogenous nature allows for the definition of diverse individuals which may differ with respect to their characteristics.

- **Rationality:** With respect to reasoning agents can be defined as rationally behaving, or their behaviour can be determined according to concepts of bounded rationality. Models adapting rational behaviour in general assume that all agents have unrestricted access to all available information about other agents and the environment. However, in some situations this representation is not appropriate. Therefore, a concept of bounded rationally has been introduced to reduce the agent's knowledge. These agents make decisions based on limited information which is obtained through interaction with others or by collecting clues from the environment (Edmonds, 1999).

- **Cognition:** Agents act according to some model of cognition that enables them to process the input information and make a decision on how to react. Such cognition models divide agent control into reactive and proactive sometimes also called deliberative. Reactive agents only respond on a stimulus and their behaviour is driven by fixed situation-action rules which remain constant during the simulation process (Jonker and Treur, 1998). In contrast, pro-active agents are capable of generating their own unique behaviour when either the situation demands, or the opportunity arises. Such agents apply complex reasoning which results in adoption of the most favourable set of actions which help them to achieve the selected goal.

- **Mobility:** Agents can be given the ability to move in the simulation environment and therefore change their locations over time. The mobility can be associated with human-like movement from one location to another, or as the ability of an agent to transport itself between various computers on a network. The movement of each agent is determined by a set of navigational rules.

- **Social ability:** Agents are capable of interacting and communicating with each other. Communication enables them to exchange information and therefore learn more about the situation they reside in.

2.2.2 Geo-simulation of Social Systems

According to Johnston et al. (2006) a system is a group of elements organised such that each one is in some way interdependent (either directly or indirectly) with every other element. If the elements represent people, the system can be called society or a social system. Each system is organised around a specific function, goal or a purpose. In the case of a social system, these are characterised by the nature of the people who form the system, their behaviour, relations, and mutual interactions.

Due to their complexity and diversity social systems are very challenging to model (Itami, 1994). According to Maguire (2005) some of these challenges are related to:

- generalisation of the system to eliminate details which are not relevant for a particular perspective from which the system is being modelled;
- identification of the effective and efficient way the system can be represented;
- defining principles by which the functionality of the system can be described and explained; and
- identification of the most appropriate approaches for simulating the processes involved in the system.

In recent years, many researchers have pointed out that ABM has a large potential to overcome some of these challenges (Bennett and Tang, 2006; Axelrod, 2007; Crooks et al., 2007, 2008). To date a number of projects have been conducted to explore potential of ABM for modelling social systems. For instance, several models have been developed for prediction and analysis of residential mobility in big cities over various periods of time (e.g. Batty, 2005; Crooks, 2007; Benenson, 2004). Heppenstall (2004) applied ABM technology to predict changes of petrol prices using West and South Yorkshire as a use case study area. Numerous studies were also conducted to explore the investigative ability of this simulation approach. ABM has for instance been successfully applied to exploration of effects caused by changes to parking policies in Tel Aviv (Benenson et al., 2007), or to examine impact of tourists behaviour on landscape in the Broken Arrow Canyon national park in Arizona (Gimblett et al., 2002).

2.2.2.1 Sense of Space and Place

Social systems are embedded in geographical space, therefore mutual interactions between the system entities (people, housing market, etc.) is to a large degree influenced by the physical environment in which they reside. Benenson and Torrens (2004) argue that ABM could be used to better understand these complex interactions. They have associated design and construction of models for exploration of ideas and hypotheses about processes with geographic context geo-simulation. This term is used throughout the whole thesis to emphasise the importance of considering geo-spatial aspects in models depicting social systems.

According to human geographers human behaviour is influenced not only by *space*, which depicts the characteristics of the environment, but also by *place* which is related to cognition of the area by each individual (Johnston et al., 2006). Therefore, while space is seen as a universal, more abstract phenomenon, the concept of place is associated with an individual's attachments to particular locations. This also means that a single location can have different effects on different people. Such influence of physical places, i.e. *sense of place* is reflected as a feeling of a person about the specific area which is a combination of:

- how an individual perceives the area (for instance the location is connected with significant events from the person's past);
- feelings generated by direct interactions with other people (e.g. forming crowds, stampede, panic, etc.); and

- the influence of the actual physical space (street feels too narrow, high buildings, unfamiliar area, etc.).

Batty (2003a) indicates that if the geo-simulation model is to represent social behaviour at the micro scale level, i.e. at the level of streets and buildings, the central activity which needs to be considered is the *movement* of individuals. Jiang and Gimblett (2002) argue that the movement is affected by the social interaction with others and the influence of the environment (consisting of *sense of space and place*). Hence, the geo-simulation models need to consider the movement from both of these perspectives (Batty, 2003b). However, to date, the focus has been mostly oriented towards the social context of the behaviour (Davidsson, 2001). This suggests that more research is needed to incorporate geo-spatial aspects into the geo-simulation models.

2.2.3 Purposes of Agent-based Modelling within Disaster Management

Social systems delimited by processes, objects, events and people that are related to assessment of risks of a disaster or dealing with its consequences are grouped together under integrate emergency management (IEM) framework which is also often referenced as the disaster management (Haddow and Bullock, 2006). The range of events that could possibly be included in IEM system is extensive. In general these events represent all possible situations that can violate security of everyone's daily lives. Such situations are associated with natural, technological or man-made crises and disasters in peacetime (UK Cabinet Office, 2003). This indicates diverse potential of ABM ranging from simulating processes related to mitigation and prediction of the disaster, through decision support during the response operation, and for assessment of social and economical impact of the disaster once its immediate risks are suppressed.

Crooks et al. (2008) argue that the use of agent-based models is no longer restricted to the development of mechanisms for testing scientific theories. Their scope and purpose has in the last two decades broadened. Castle and Crooks (2006) generalised the use of ABM into:

- **Exploration:** to investigate a specific theory and generate a set of hypotheses about the modelled system by placing emphasis on some details while ignoring others.
- **Prediction:** to identify emergence of a system to forecast its possible future states by evaluating different scenarios and their effects on the model outcomes.

Similarly, Axelrod (2007) argues that ABM can be useful to predict emergence of a specific phenomenon. He further sub-divides the category of exploratory models into models used for:

- **Performance:** to model decision making tasks mimicking human reasoning (medical diagnosis, speech recognition, function optimisation, etc.) or to test application of artificial intelligence techniques for solving real-life problems.
- **Training:** to provide a reasonably accurate and dynamic interactive representation of a given environment to enable testing different approaches to resolving the simulated problem or situation.
- **Entertainment:** computer simulations used in a gaming industry.
- **Education:** for experimentation allowing users to learn relationships and principles embedded within a specific system.
- **Proof:** to seek for a proof of a certain theory or as a methodological approach to evaluate scientific hypotheses.
- **Discovery:** to identify and explore new relationships and principles.

This categorisation has been established to accommodate the broad spectrum of geo-simulation models without considering the nature of the systems they

	Abbreviation	Further description
Model purpose	PRE	Prediction
	PER/OPT	Performance or optimisation
	TR/ED	Training or education
	EXP	Exploration
Model type	CB	Crowd behaviour
	MSP	Multi-simulation platform
	RC	Response coordination
	EVAC	Evacuation
	PROP	Propoagation

Table 2.1: Key of abbreviated terms used in Table 2.2 and Figure 2.1.

model or the area of their utilisation. This very general specification can become rigid when investigating the purpose of models developed for a single application domain. The two classifications have been combined into four categories to reflect the existing trends in application of ABM to disaster management. Therefore, they have been defined with consideration of the reviewed scientific publications.

- **Prediction:** to forecast system emergence under specific conditions or for discovery of new unexpected patterns.
- **Performance or optimisation:** to improve simulation performance or for testing state-of-the-art algorithms and processes.
- **Training or education:** for training and education of response personnel, or for evaluation of newly proposed scientific frameworks.
- **Exploration:** to investigate different approaches to disaster management related activities, or for their optimisation.

In order to identify trends in current development of ABM within disaster management the selected models were organised according to these four purpose categories in Table 2.2 (see Table 2.1 for the key of abbreviated terms). The classification is based on the author's understanding of the model purpose. If not specified the model was assessed based on information extracted from the text.

To gain closer insight each model is briefly described and the use case on which the model was tested is specified if stated. Table 2.2 also contains information regarding the type of the model which is specified by the nature of the real-life system it represents. This categorisation was created based on information obtained from the reviewed publications. The model types are as follows:

- **Crowd behaviour:** for studying the nature of crowd dynamics, i.e. understanding behaviour that leads to formation of crowds (Still, 2000). In addition, the model can be developed for assessment of crowd safety and for evaluation of strategies related to its control and prevention of congestions.

- **Multi-simulation platform:** combination of several simulators (fire propagation, crowd behaviour, search and rescue, etc.) to gain bigger picture of the disaster situation.

- **Response coordination:** to facilitate coordination of distributed emergency response teams. This model type can also be used for optimisation of response strategies, or as a decision support tool for prioritisation of standard operating procedures which need to be followed during the response.

- **Evacuation:** to simulate realistic behaviour of evacuating pedestrians. Moreover, this model type can be used for identification of the most common behavioural patterns of evacuees, or for investigation of impact of different evacuation strategies.

- **Propagation:** to study propagation of an infectious disease or a contaminant among the population, or spread of fire from one building to another.

To enable visual comparison of the models, the outcomes of the analysis are graphically displayed as bar charts in Figure 2.1. As indicated in bar chart a) the majority of the models represented evacuation scenarios from enclosed areas (e.g. underground systems Castle, 2007or buildings Murakami et al., 2002)

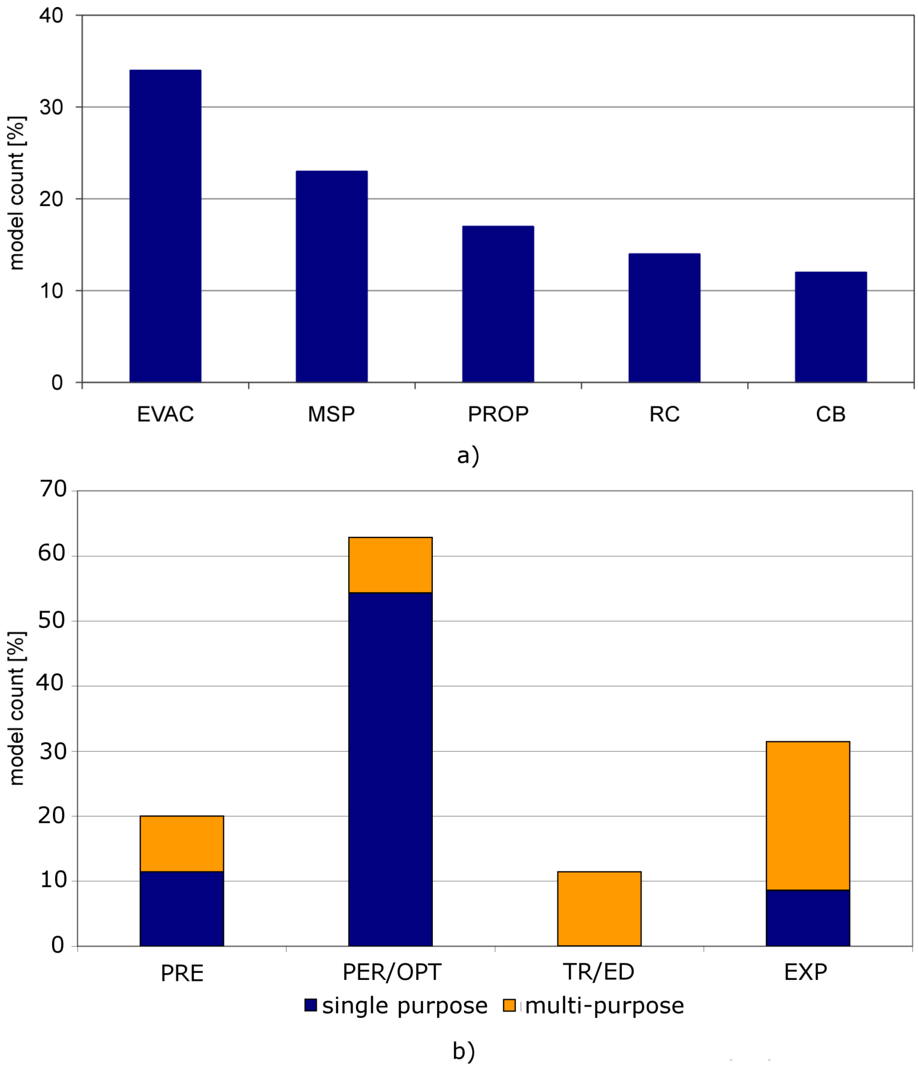

Figure 2.1: Organisation of the reviewed models according to their type a) and purpose b) (see Table 2.1 for the key of abbreviated terms).

or on a street (e.g. Shendarkar et al., 2006). The frequencies of models from the remaining type categories range between 23 % and 12 %. Although 26 % of the models were developed as multi-purpose the bar chart b) reflects that the majority of the models have been implemented with a focus on one specific purpose (74 %). This indicates diversity and complexity of some of the purpose categories as it is further discussed throughout this section.

None of the reviewed models were intended to be used purely as a training or educational tool. Such purpose was only considered in combination with *exploration* and *performance or optimisation*. The *performance or optimisation* was identified to be the most common purpose of the assessed models (63 %). In majority of the cases this has been the only intention. Although *exploration* was the second most common purpose it was often coupled together with another category. Finally, 20 % of the reviewed models were intended for *prediction*. However, almost half of these models were implemented also for other purposes.

The purpose of the models is further discussed in following sections. Firstly, the multi-purpose models are assessed followed by the critical evaluation of the single purpose models. The main intentions of the discussion are to:

- identify what are the specific reasons for development of the geo-simulation models within each purpose category; and
- evaluate whether the implemented models correspond with the purpose for which they have been originally intended.

Table 2.2: Categorisation of the reviewed models according to their purpose.

Key reference	Model type	Description	Case study	Purpose			
				PRE	PER/ OPT	TR/ ED	EXP
Banarjee et al. (2005)	CB	application of ant colony optimisation algorithm to analyse behaviour of panicked crowd	observation of panic in several hypothetical cities affected by a war		√		
Batty et al. (2003)	CB	simulation of effects of changing the route of a street parade	Notting Hill Carnival	√			√
El Rhalibi and Taleb-Bendiab (2006)	CB	application of an improved agent architecture to study crowd behaviour	political street protest		√		
Ulicny and Thalmann (2002)	CB	development of a real-time crowd simulation to train people to efficiently react to explosions	bomb explosion on a street		√	√	
Braun et al. (2005)	EVAC	combination of characteristics of a model proposed by Helbing et al. (2000) and concepts presented in Braun et al. (2003)	impact of an alarm system on the building evacuation		√		√

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Key reference	Model type	Description	Case study	Purpose PRE	PER/ OPT	TR/ ED	EXP
Castle (2007)	EVAC	development of a framework for investigation of a wide range of emergency evacuation scenarios from a tube stations	King's Cross/ St. Pancras station	√			√
Helbing et al. (2000)	EVAC	investigation of the mechanisms that trigger panic and jamming by uncoordinated motion in evacuation	smoke-filled room evacuation				√
Henein and White (2007)	EVAC	extended model presented by Kirchner and Schadschneider (2002) of additional crowd forces and injuries they cause	room evacuation		√		
Hu (2006)	EVAC	application of a context-dependent behaviour selection architecture to generate realistic human behaviour	fire alarm in a museum		√		
Murakami et al. (2002)	EVAC	implementation of evacuation behaviour defined by Sugiman and Misumi (1988)	evacuation from a basement		√		
Musse et al. (2007)	EVAC	automated extraction of pedestrian movement from video sequences	panic after an explosion on a t-shaped junction		√		
Raupp-Musse and Thalmann (2001)	EVAC	development of algorithms for real-time simulation of crowd behaviour	evacuation from a museum exhibition		√		
Pan et al. (2007)	EVAC	studies of non-adaptive crowd behaviour	building evacuation		√		
Shendarkar et al. (2006)	EVAC	management of evacuating crowds after a lorry bomb explosion	National Mall area in Washington DC	√			√
Still (2000)	EVAC	development of more appropriate risk analysis methodology for the design and management of areas vulnerable for crowding	Wembley Stadium, Balham Station and Hong Kong Jockey club	√			
Zarboutis and Marmaras (2007)	EVAC	development of a methodological framework for the design and implementation of models used for formation of evacuation plans	flaming tube carriage stalled between two stations in Athens tube system			√	√

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Key reference	Model type	Description	Case study	Purpose			
				PRE	PER/ OPT	TR/ ED	EXP
Adams et al. (2008)	MSP	introduction of decentralised system architecture for emergency response coordination; partly using RoboCup Rescue platform	n.a.		√		
Farinelli et al. (2003)	MSP	extension of RoboCup Rescue platform of additional components; introduction of cognitive agent development framework; presentation of methodology for evaluation of RoboCup Rescue related models	earthquake in Kobe City, Japan, 1995		√		
Habibi et al. (2002)	MSP	extension of RoboCup Rescue platform of additional components; introducing new learning and task allocation algorithms to agent reasoning process	earthquake in Kobe City, Japan, 1995		√		
Kitano et al. (1999), Takahashi et al. (2002) and Takahashi (2006)	MSP	introduction of RoboCup Rescue platform	earthquake in Kobe City, Japan, 1995		√		
Kleiner et al. (2006)	MSP	extension of RoboCup Rescue platform of additional components; real-time data update	data integration from hypothetical incident site in Bremen, Germany		√		
Raymond and Reed (2006)	MSP	extension to the RoboCup Rescue platform of additional components; introducing a new type of agent	earthquake in Kobe City, Japan, 1995		√		
Reinaldo et al. (2005)	MSP	extension of RoboCup Rescue platform of additional components; application of neural networks to agent's reasoning	earthquake in Kobe City, Japan, 1995		√		
Visser et al. (2004)	MSP	extension of RoboCup Rescue platform of additional components; self-organisation of agents	earthquake in Kobe City, Japan, 1995		√		

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Key reference	Model type	Description	Case study	Purpose			
				PRE	PER/ OPT	TR/ ED	EXP
Carley et al. (2006)	PROP	simulation of the effects of weaponised biological and chemical attacks; contains characteristics of various dangerous substances enabling implicit identification of the one used in the attack	anthrax attack on a hypothetical city	√			
Eubank et al. (2004)	PROP	simulation of a smallpox spread	hypothetical scenario of smallpox outbreak in Portland, OR				√
Mysore et al. (2005)	PROP	exploration of assumptions about public health policies and emergency preparedness	food poisoning in Minas Gerais, Brazil, 1998	√			
Mysore et al. (2006)	PROP	simulation of human response to a CBRN incident	hypothetical Sarin gas attack at the Port Authority Bus Terminal in New York	√			
Rahmandad and Sterman (2008)	PROP	simulation of spread of an infectious disease	experimentation with five different network structures		√		
Roche et al. (2008)	PROP	simulation of spread of a vector-borne disease transmission in realistic spatial environment	n.a.		√		
Buford et al. (2006)	RC	scalability of distributed processes	coordination of medical relief operation;		√		
Farinelli et al. (2004)	RC	application of RoboCup Rescue platform to support decisions of first responders and monitor response operation	earthquake in Umbria-Marche, Italy, 1997		√		√
Schurr et al. (2005)	RC	improvement of human collaboration with agent teams	coordination of response to large fires			√	√
Wagner et al. (2003)	RC	coordination of distributed emergency response team	fire in a ten-storey hotel				√
Wickler et al. (2006)	RC	coordination of emergency response team with respect to standard operating procedures	hypothetical scenario related to recovery from a major incident arising from a miliary operation			√	√

2.2.3.1 Multi-purpose Models

The majority of the multi-purpose models were partly developed for exploration. The exploration is of various forms depending on what is the other intention of the model. For some of the models exploration was the primary purpose while for others it was seen as a means for evaluation of the model technical capabilities. Table 2.2 indicates that exploration models have been coupled with purposes from all three remaining categories, i.e. prediction, performance or optimisation, and training or education.

It is not always easy to collect all necessary information in such level of detail that would satisfy the demand on quality required on purely prediction models. It is often the case that such models are also used for exploration. In this instance the exploration purpose is related to evaluation of the impact different settings of model parameters have on the simulation outputs. The reliability of these multi-purpose models is dependent on the approach adopted for their implementation.

For instance, the behaviour of agents in model depicting movement of spectators during Notting Hill carnival (Batty et al., 2003) and the KXPEM tool simulating evacuation from an underground railway station (Castle, 2007) is defined with consideration of real-life data collected during historical events that occurred at the same locations (footage of the previous year carnival, evacuation drill data and reports on the 1987 fire in the King's Cross St. Pancras station). Incorporation of such information makes the simulated scenarios more realistic for both purposes, i.e. prediction of pedestrian behaviour during future events and for investigation of impacts of various response scenarios (e.g. redirection of the crowds to different roads, evacuation). However, utilisation of such information was not considered in explosion evacuation model developed by Shendarkar et al. (2006). This indicates that the model is a prototype developed for testing initial ideas. However, it is not robust enough to satisfy the needs of the emergency planners. Such difference in reliability between the models demonstrate that their application to real-life decision making processes is limited.

Exploration in connection with performance or optimisation purposes was mostly seen as a secondary intention. However, the approach to exploration remains the same as in the previous paragraphs i.e, identification of the most appropriate strategies for evacuation or response to an incident. The previously reviewed models, were tested within (i) real environments and with (ii) realistic settings of the key model parameters such as the number of agents, behaviour of agents etc. (with an exception of Shendarkar et al. (2006)). In this category the model developers did not always consider correctness of both of these settings important.

This category contains two models: a building evacuation model by Braun et al. (2005) and a model of a response coordination implemented by Farinelli et al. (2004). From the technological perspective both of these models used already existing architecture which they aimed to enhance with additional features to improve the behaviour of agents of complex reasoning to more closely represent decision making of people in the similar situation. However, since the utilisation of the real-life information was in both cases limited their exploration purposes have not been yet fully achieved.

Three models were developed as an alternative environment for training response personnel for large emergencies. At the same time the results of these models can also help the junior incident commanders to evaluate impact of their decisions on the progress of the response operation. The exploration in these models is a secondary consideration mainly providing a feedback on the user defined strategy.

The model developed by Wickler et al. (2006) was several times successfully tested during real response exercises. These were however related to military operations rather than natural or man-made disasters involving cooperation of blue-light services. Although DEFACTO model (Schurr et al., 2005) and model presented by Zarboutis and Marmaras (2007) were developed in cooperation with the potential users to maximise their usability, no information was provided whether they were successfully integrated for education of fire and rescue personnel or the underground railway security staff respectively.

The tool developed by Ulicny and Thalmann (2002) is the last remaining multi-purpose model which was not yet discussed. It is also the only one which is not partly implemented for exploration purposes. Although the main focus of the research project was to improve the overall model performance, it was tested as a potential training environment to teach people how to react to an explosion. Since the use case depicted only a hypothetical situation where behaviour of the agents did not correspond with reality, it would not in its current state be suitable for education.

2.2.3.2 Performance or Optimisation

The majority of the reviewed single purpose models were developed purely for improvement of agent performance or state-of-the-art algorithms. This clearly demonstrates that disaster management was utilised as an interesting and purposeful domain for testing new ideas. This is mainly due to the highly dynamic nature and complexity of the underling processes. The 19 corresponding models can be further categorised into four groups based on the components of the agent-based system they focus on improving. The groups together with references to the models are presented in Table 2.3.

Performance and optimisation models were not intended to represent real-life situations. As a consequence the behaviour of agents does not fully correspond

Category	Key reference
Application of artificial intelligence (AI) algorithms	Banarjee et al. (2005), Habibi et al. (2002), Reinaldo et al. (2005), Visser et al. (2004)
Optimisation of the model performance	Raupp-Musse and Thalmann (2001)
Enhancement of the model architecture	El Rhalibi and Taleb-Bendiab (2006), Adams et al. (2008), Farinelli et al. (2003), Kitano et al. (1999), Takahashi (2006), Takahashi et al. (2002), Kleiner et al. (2006), Rahmandad and Sterman (2008), Buford et al. (2006), Hu (2006), Roche et al. (2008)
Representation of complex human behaviour	Henein and White (2007), Murakami et al. (2002), Musse et al. (2007), Raymond and Reed (2006), Pan et al. (2007)

Table 2.3: Categories of models developed for improving simulation performance and optimisation.

to the reactions of real people. Some of the selected use cases (e.g. a "live" statue chasing panicked crowd; Musse et al., 2007) are not even related to a situation which could be anticipated in real life. The credibility of the model however lies in the technical specification of the agent's architecture with respect to the overall model performance. Hence, the models should be only evaluated from that particular perspective. This highly limits their utilisation to facilitate work of emergency management domain experts.

Four models concentrated on combining geo-simulation capabilities with principles of AI to advance the behaviour of agents of more human-like characteristics. Banarjee et al. (2005) and Visser et al. (2004) applied ant colony optimisation algorithms to study principles of self-organisation of crowds and Habibi et al. (2002) and Reinaldo et al. (2005) focused on improving an agent's interaction with the environment by introducing learning algorithms into its decision making. Although the purpose of these projects was to demonstrate that AI algorithms can provide better mechanisms for agents to cope with unforeseen events, evidence that could prove this claim was missing. The simulation results were not compared with other models to highlight the advantages of this approach even at a conceptual level.

Raupp-Musse and Thalmann (2001) presented the only model specifically intended to improve the simulation performance in order to enable real-time simulation of crowd models used in film or game industry. This was achieved by representing the scenario on various levels of detail allowing for changing between behaviour of individuals at the small-scale and interaction of groups at the macro level. The model architecture was only tested as a stand alone system. Therefore, it is very hard to conclude whether it could, in its current state, bring any advantages once incorporated into a computer game or a film as originally intended.

The majority of models that were aimed at improving overall structure of the model or an agent architecture concentrated mainly on advancing a specific algorithm or process within the whole system. Since developing the model from scratch would cost too much time and resources it was found more desirable to use already existing simulation frameworks for the experimentation. The RoboCup Rescue platform has been actively used in recent years for such purposes. It combines a number of various heterogenous agent simulators to more realistically represent a character of a large disaster (Kitano et al., 1999; Takahashi et al., 2002; Takahashi, 2006).

The use case RoboCup Rescue simulates is defined with data obtained from Kobe-Awaji earthquake in Japan, 1995. However, the historical data are only used for initialisation of the simulation. Hence the number of injured or trapped people, structural collapses, buildings in fire, and number of search and rescue units are defined with accordance of the historical disaster. However, the rules that guide behaviour of the agents representing civilians and the blue-light services, together with rules depicting the propagation of fire or building collapses are purely hypothetical.

The majority of the researchers who use the RoboCup Rescue platform concentrated on improving its performance capabilities (e.g. fusion of information generated by the different simulators; Adams et al., 2008 and Farinelli et al., 2003). The advanced models are presented in annually organised contests which aim is to identify the optimal rescue strategy for the Kobe disaster. The competing models are evaluated according to the time required for the blue-light services to rescue trapped and injured civilians. Although the robustness and complexity of such models can be of valuable asset to the disaster management experts the unrealistic behaviour of the agents preclude their wider application in real-life situations.

Several researchers made an attempt to overcome this shortcoming and focused on practical application of the RoboCup Rescue platform. For instance Farinelli et al. (2004) tested flexibility of the model to utilisation of data describing different use case. Research conducted by Kleiner et al. (2006) looked at incorporation of real-life information about the state of the incident through data streams from the incident site. Even though both of these research projects were oriented towards the technological side they demonstrated that this multi-simulation platform has a strong potential to support real-life incident response coordination.

The capabilities of multi-platform technology was also tested by Buford et al. (2006). While the focus of the majority of RoboCup Rescue publications was put on advancing a single simulator this research concentrated on resolving issues related to the simulator integration. Although the paper provided a detail description of all components of the very complex model architecture it was not reported whether the model has been implemented and tested. Limited information related to evaluation of the proposed changes and whether they have improved the existing state-of-the-art was also been provided in the remaining publications which aimed to demonstrate advantages of ABM over differential equations models in epidemiology (Rahmandad and Sterman, 2008; Roche et al., 2008) and to test complex multi-tier agent architectures (Hu, 2006; El Rhalibi and Taleb-Bendiab, 2006).

Different approaches were adopted for studying representation of complex human behaviour by computational algorithms. These models are still different from models implemented for prediction or exploration (discussed in the following sections). Probably the most significant difference is that these are tested on often simplified scenarios e.g. limitation of evacuation only to a single room (Murakami et al., 2002). One possible method is to couple ABM with techniques of AI as it was already discussed.

Another approach is to automatically extract behavioural information from camera or a video footage capturing the real-life situation. For instance, Musse et al. (2007) integrated computer vision algorithm to feed a crowd model by automated extraction of pedestrian behaviour from a video sequence. This approach proved to be very successful. However, its capabilities are only limited to simulation of situations that were capture on a video. Such material depicting emergency situation does not always exist. In addition, this technique is applicable to a small area which is for instance delimited by a range of one CCTV camera. Therefore, it can be only applied for highly localised emergencies.

Three publications (Raymond and Reed, 2006; Henein and White, 2007; Pan et al., 2007) concentrated on advancing already existing agent's architectures of more human-like characteristics. The improvements were evaluated by comparing the results generated by the new model with the original one. However, it was not discussed whether the changes led to more effective representation of human-like behaviours. This suggests that the focus was put on increasing complexity of the model by enhancing the agent's behavioural algorithms using emergency scenarios only as an interesting testing use case.

2.2.3.3 Exploration

As was already discussed in review of the multi-purpose models, exploration can have many different forms. In this section the focus is put on exploration of patterns emerging from the simulation outcomes. With this respect two approaches emerged from the reviewed literature. In the first approach a mechanism by which the simulation outputs are evaluated is implemented as a part of the model (Wagner et al., 2003, e.g. TÆMS;). This model contains an optimisation algorithm that assesses the results and automatically resets the parameters towards the optimal solution. TÆMS was tested on coordination of a response to large building fires. To ease the complexity only a subset of the response was represented. Hence, its application to complex real-life emergencies is limited. In addition, the list of tasks and their priorities would have to be changed if the model was applied to a different type of incident.

Since the changes to the parameters are done automatically, this approach is capable of running a large number of simulations without any additional user input. This is also its drawback since the user loses the control over the model. In some situation it is much more desirable to define the model parameters to test a specific situation which is meaningful in the context of the modelled system. This does not necessarily have to be the most optimal solution from the computational perspective.

In this second approach the model is implemented in such a way that enables simple and effective alteration of the parameters after each simulation run. The outputs of the simulation are then evaluated with the use of additional mechanisms that are not part of the model. This approach was adopted by Eubank et al. (2004) and Helbing et al. (2000). The former investigated effects of different vaccination strategies on propagation of smallpox, the latter focused on identification of the optimal evacuation from a smoke-filled room. While Eubank et al. (2004) defined the scenarios to correspond with procedures that would be applied in real-life if the epidemic strikes, the parameterisation of the evacuation model was not based on any reported evacuation strategies. Although Helbing et al. (2000) claimed that the developed model provided the same results as were observed during evacuation drills. This however does not verify that the underlying processes are realistic.

2.2.3.4 Prediction

If the model is developed to predict emergence of a real-life system in time, it needs to be defined with consideration of the system specific information. This information is related to:

- realistic representation of behaviours the entities forming the system perform;
- accurate parameterisation of the model as well as realistic representation of agent's attributes (Crooks et al., 2008);
- correspondence of the simulation space with the environment of the real-life system (Castle, 2007);

Crooks et al. (2008) argue that the most optimal way to assess the reliability of the predictive model is to compare its outputs against data obtained by analysis of past disasters of a similar nature. Application of these models on different scenarios may jeopardise the accuracy of the prediction and can lead to deceptive conclusions about the progress of the modelled situation. However, only Still (2000) considered data from historical incidents during implementation of the model for prediction of crowd dynamics in enclosed spaces (stadium, station or a club).

Similar to the RoboCup Rescue Mysore et al. (2005) only considered information regarding the historical event for population of the initial state of the simulation (food poisoning outbreak in Minas Gerais, Brazil, 1998). The behaviour of the ambulance units as well as the hospital agents have not been defined according the real situation in their following model predicting requirements for decontamination of victims affected by Sarin gas attack in Manhattan (Mysore et al., 2006). In this model no reference to sources which were consulted for parameterisation of the model and definition of the behaviour of the different types of agents was provided. It is therefore assumed that these were also only hypothetical. This indicates that although these two models were developed for predictions they do not fulfill the required qualities and are therefore not usable in this sense.

Although model developed by Carley et al. (2006) was also based on a hypothetical scenario, the parametrisation of agent is based on census data. This data together with additional medical records were used to realistically represent the characteristics of the modelled population with respect to their vulnerability to the simulated bio-terrorism attack of smallpox or anthrax. Similarly, Still (2000) characterised the behaviour of agents to correspond with behaviour of football supporters which was captured on a video footage from the Hillsborough disaster in 1989. This makes the model more suitable for prediction purposes since it was validated against historical scenario.

2.3 Development of Geo-simulation Models for Disaster Management

This second part of the literature review discusses problems and issues which are connected with development of geo-simulation models for disaster management. Section 2.3.1 concentrates on identifying aspects which consideration forms an important part during such development process. The definition of these aspects is based on review of scientific literature which provides suggestions on how to generalise complex social systems into a geo-simulation model. A set of questions related to each aspect is formed by which the selected 35 models are evaluated. This provides closer insight into the problems and issues consideration of these aspects brings to the development process (Section 2.3.2).

2.3.1 Aspects Related to Geo-simulation Model Development

Development of a geo-simulation model consists of a significant number of processes where some of them influence the quality of the final product to a greater degree than others. For instance, implementation of a robust graphical user interface (GUI) can facilitate user interaction with the system. However, GUI is not a crucial component without which the model can not operate. Much more significant impact on the model quality has for instance the accuracy of the behavioural algorithm agent executes each step of the simulation experiment. The amount of time spent on each step of the model development is for each developer or researcher to judge. The distribution of time should correspond with

- the resources available for the model development,
- the focus or interest in specific method or area of the development process, and
- the purpose of the final model (as defined in Section 2.2.3).

As a consequence of the diverse focus and purposes no uniform and generally accepted process of developing an agent-based model for disaster management exists. Recently several researchers recognised this issue and published articles which (i) highlighted challenges ABM poses with respect to geo-simulation of social systems (Axelrod, 2007; Crooks et al., 2008) (ii) provided methodological frameworks to facilitate the development process (Benenson and Torrens, 2004; Zarboutis and Marmaras, 2007), or (iii) developed a framework for assessing existing models regarding their reuse for different situations (Castle, 2007). The collected information is summarised in Table 2.4.

Table 2.4: Summary of concerns during geo-simulation model development.

Source	Concern	Explanation
Benenson and Torrens (2004)	type	defining actors of the simulation; determining abstraction of the modelled system
	states	definition of all possible behaviours of an agent
	transition rules	description of changes in agent's state; definition of conditions that trigger these changes
	location	reference of an agent to the simulation space; scale; data format
	movement rules	navigation of an agent on the simulation space
	neighbours	definition of spatial relationship between agents that can mutually interact
	influence of neighbours	interaction between agents
Axelrod (2007)	programming simulation model	selection of an appropriate programming language; validity (correct implementation of conceptual model), usability (understanding how the model works) and extendibility (adaptability of the model for other use)
	analysing the results	data collection perspective (chronological order, view point of one actor, global); need for several simulation runs to depict typical situation (statistical analysis) - possible to observe influence of model parameters on resulting patterns
	sharing the results	reasons: sensitive results - need for detail description; results need to include narrative description of the adopted perspective; interdisciplinary audience; new technique need careful explanation;
	replication	confirmation whether generated results are reliable in a sense that they can be reproduced from scratch
Castle (2007)	availability & access	how can be the model obtained; cost of the model; requirements on operating system, software and hardware
	purpose/ background	fitting the purpose of use; appropriate level of detail; origin of the model (expertise of the developer)
	nature	representation of behaviour and social attributes
	enclosure representation	scale of the environment; format of used data (e.g. CAD, GIS, image file)
	occupant/ enclosure perspective	global of individual level of pedestrian representation (aggregate or individual-based models); what information is available to the agent about the environment
	occupant movement	speed definition, origin and validity; definition of navigation and movement
	behavioural perspective of occupants	reasoning mechanism of agents; scale of behaviours
	validation	model documentation; limitation and capabilities of the model; reliability
	support	availability of training courses, tutorials; help; bug reporting/fix

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Source	Concern	Explanation
	initial analysis	understanding the application domain and its problems;
Zarboutis and Marmaras (2007)	determination of system boundaries & identification of comprising wholes	determining abstraction of the modelled system; defining characteristics of an agent
	modelling: (i) level of abstraction (ii) agent type	(i) level of modelled detail (ii) validity of agent's behaviour with respect to real system entities
	agent-based simulation	selection of programming language or modelling environment; determining degree of validity in generated data; selection of a method for result assessment
	application of results	investigate efficiency of the model application for selected purpose
(Crooks et al., 2008)	purpose	intention for which the model is developed; level of modelled detail
	theory & model	knowledge of theoretical implications of the model; acquisition of domain knowledge; use of domain specific data
	replication & experiment	testing different types of models or different variants of the same model (e.g. use of a different data set); evaluation of model robustness
	verification, calibration and validation	evaluating correctness of implemented algorithms; fine tuning of model parameters to match the real-life situation; evaluating credibility of the results
	agent representation, aggregation & dynamics	definition of agent's abstraction, behaviour and characteristics; determine agent's movement and interactions
	operational modelling	possibility of reproduction of simulation outcomes; extendibility; application to other research projects; use of modelling environments; selection of programming language
	sharing and dissemination of the model	accessibility of the model; possibility to embody the model into existing programs

Although ABM is highly multi-disciplinary a need for a uniform development framework has been recognised predominantly by researchers with geographic background. Although from a single scientific discipline, the authors have different research interests ranging from urban dynamics (Castle, 2007; Crooks et al., 2008), advancing theories of geospatial modelling (Benenson and Torrens, 2004), to application of principles of human geography to other disciplines (Axelrod, 2007). In addition, the perspective adopted by Zarboutis and Marmaras (2007) is of highly specific nature due to their background in mechanical engineering. Hence, review of these publications enables to gain insight into the development process from wider perspective. Since all of these publications were peer-reviewed (scientific journals and PhD thesis) it indicates that discussions related to such matter have been recognised by ABM experts as important.

Although all five publications specifically concentrated on development of models representing complex social systems, the opinion of their authors on what considerations need to be addressed hugely differ (see Table 2.4). For instance Axelrod (2007) only focused on aspects that should be considered after a conceptual model of the simulation is developed. However, Zarboutis and Marmaras (2007) argue that in order to implement a successful geo-simulation model the process should start with familiarisation with the application domain for which the model would be used. This could provide further insight into the domain related problems and issues which the model can help to resolve.

To be able to compare and contrast the proposed approaches and suggestions the whole spectrum of considerations discussed in the publications were organised into five aspect categories in Table 2.5. In the following sections each of the aspects is further discussed. The organisation into the five categories was not without any problems. Often very different considerations and opinions had to be incorporated into a single aspect category. Nevertheless, the probably most prominent lesson learned emerging from all publications is related to importance of keeping the behaviour of the modelled system in accordance with its real-life counterpart.

Source	Based on	Why?	Understanding the Application Domain	Human Behaviour Representation & Parameterisation	Environment Representation & Sense of Space and Place	Reasoning Process	Results Analysis & Model Evaluation	Evaluation of Proposed Guidelines/ Framework
Benenson and Torrens (2004)	not stated	provide methodological framework	no	(i) agent type (ii) transition rules (iii) interaction	(i) scale (ii) data format (iii) reference of an agent to the environment (iv) navigation (v) neighbours	transition rules	no	suitability discussed with reference to 35 models and illustrated on implementation of OBEUS
(Axelrod, 2007)	(Axelrod, 1997)	highlight aspects that need to be considered once conceptual model exists	no	selection of programming language			(i) validation (ii) usability (iii) analysing the results (iv) replication (v) sharing the results (vi) extendibility	demonstrated replication on 8 models
Castle (2007)	Nelson and Mowrer (2002)	assess existing models	(i) software and hardware requirements (ii) original purpose (iii) availability & cost	(i) sufficient level of detail (ii) scale of behaviours & agent's attributes	(i) scale (ii) data format (iii) navigation & movement (iv) rationality	(i) cognition model (ii) action selection mechanism	(i) validation (ii) capabilities & limitations (iii) reliability (iv) training and support (v) documentation	evaluated 27 models
(Zarboutis and Marmaras, 2007)	complex adaptive systems modelling	provide methodological framework	(i) familiarisation with the basic domain properties (ii) in depth understanding of the problems	(i) system boundaries (ii) level of detail (iii) selection of programming language or modelling environment (iv) characteristics of an agent	no	no	(i) validation (ii) determining method for results assessment (iii) efficiency of the model application	model of fire in a tube tunnel
Crooks et al. (2008)	Axelrod (2007)	identify challenges involved in development	(i) purpose (ii) theory & model	(i) level of detail (ii) use of domain specific data (iii) agent representation (iv) interaction (v) programming language or modelling environment	agent's movement	no	(i) verification & calibration & validation (ii) replication & experiment (iii) sharing & dissemination (iv) extensibility (v) further application	3 different urban models

Table 2.5: Aspects to consider when developing geo-simulation models for disaster management.

2.3.1.1 Understanding the Application Domain

As in any other software development process one of the most crucial tasks is to extract the requirements on what the final product should do. In addition, it is also important to gain closer understanding of the processes that need to be depicted in the geo-simulation model. This need for the domain related information was recognised by three of the five reviewed publications (Castle, 2007; Crooks et al., 2008; Zarboutis and Marmaras, 2007).

Zarboutis and Marmaras (2007) and Crooks et al. (2008) argue that acquiring domain knowledge can support communication with the domain experts. Such approach can facilitate identification of areas that could benefit from application of ABM and to determine for what purposes the model could be developed. Crooks et al. (2008) have highlighted that many recent models are implemented without any consideration of the application domain problems and structure of its related processes. These are often replaced by *ad hoc* assumptions which are in many cases not clearly specified. Consequently, lack of this information preclude identification of quality and usability of these models. Although Crooks et al. (2008) highlighted this issue as one of the key challenges ABM faces they did not provide any suggestions on how to overcome it.

A set of guidelines on how to learn more about the domain specific system was provided by Zarboutis and Marmaras (2007). Since these guidelines were specifically tailored to description of a very specific problem, their reuse for understanding of other systems in disaster management is limited. Even though the guidelines definition was based on hierarchical task analysis[1] the reasons for utilisation of this method for description of the system were not discussed and no information concluding the advantages and shortcomings of its application was referenced.

[1] Hierarchical task analysis describes a system through hierarchical organisation of its processes into different levels of detail. Based on this structure information how these processes are performed is collected. The performance of each process is evaluated before more effective one is proposed (Shepherd, 2000).

With respect to the initial considerations Castle (2007) highlighted importance of assessing the model cost, its requirements on the operating system, hardware and software. However, he did not specify how such requirements can be collected and whether domain experts who are the potential users of the developed model should be consulted during such analysis.

Since Axelrod (2007) only concentrated on considerations that should be taken into account once the conceptual model of the system is developed no need for understanding the application domain is expressed. Hence, other literature would need to be consulted to learn how to approach the development of the conceptual model. Finally, no reference to understanding of the application domain is provided in the methodological framework proposed by Benenson and Torrens (2004).

2.3.1.2 Human Behaviour Representation & Parameterisation

All five reviewed articles discussed difficulties connected with procedures related to definition of agent's behaviour, its representation and parameterisation. However, the researchers considered this aspect in different ways. Axelrod (2007) related complexity of the model components (as they are specified in the conceptual model) with selection of a programming language by which the model is implemented. Castle (2007) stressed the importance of knowing the background of the model developer and his/her experience. However, this information is not relevant with respect to representation of the agent's behaviour.

Human behaviour representation and parameterisation can be regarded in two ways;

- definition of agent's behaviour (deciding on the agent's response to a specific situation), and

- parameterisation of agent's attributes (defining attributes by which an agent is represented, determining their value and how they change throughout the simulation)

The importance of defining behaviour of the interacting agents with respect to the behaviour of their real-life system counterparts was discussed by Crooks et al. (2008) and Zarboutis and Marmaras (2007). Crooks et al. (2008) argued that the source of information which was consulted should be clearly referenced to enable the model users to assess whether the defined behaviour is accurate enough for the purpose of use. In addition, this information is necessary to build a confidence in the model credibility. Similar concept was specified by Zarboutis and Marmaras (2007) who highlighted importance of maintaining the real-life system characteristics during the process of reduction of its complexity into the model.

Castle (2007) further tackled this issue by discussing the importance of consulting appropriate scientific literature which reports the system behaviour. He presented this approach only on one very specific component of the complex human behaviour (definition of agent's walking speed). This was the only publication that suggested how the information regarding the behaviour of the system entities can be collected.

The parameterisation of agent's attributes was discussed with respect to the purpose of the model and the scale at which the real-life system is represented Zarboutis and Marmaras (2007), Benenson and Torrens (2004), and Crooks et al. (2008). For instance, if the purpose of the model is to observe low level interaction of evacuees such as collision avoidance or change of speed, the agent's characteristics need to be defined in a way that permits such low level changes to agent's behaviour. Even though such considerations were provided, none of the publications reported how to reduce complex human characteristics into quantitative parameters and what problems this generalisation brings.

Zarboutis and Marmaras (2007) associated the concept of an agent with a person. Therefore, the focus was put on reducing the complex human personality into the characteristics that have influence on the behaviours which are captured in the model. Benenson and Torrens (2004), Castle (2007), and Crooks et al. (2008) generalised the concept allowing for consideration of aggregated groups acting as one agent. These groups for instance can contain evacuees with similar intentions, or a rescue unit comprising of several fireman operating under one control. According to Crooks et al. (2008) the decision related to specification of the agent's parameters and how they change through time should be considered together with the following:

- the number of agents (the size of the computation usually rises as the square of the number of agents);
- the quality and reliability of the information upon which the behaviours of the agents are defined;
- purpose of the model.

For instance, if the purpose of the model is to identify whether the number of fire exits is appropriate to guarantee evacuation from a building in 20 minutes, parameters related to level of energy of each agent are irrelevant given the short time interval. The energy level could for example be reflected in more general parameter such as evacuation speed aggregating gender, energy, level of fitness, etc.

2.3.1.3 Environment Representation & Sense of Space and Place

Only two publications (Benenson and Torrens, 2004 and Castle, 2007) discussed the different ways in which environment can be represented in the geo-simulation model. They argued that the decision on what data to use and how to incorporate them into the model is closely related to the size of the area of interest and complexity of the other components forming the model (e.g. definition of agent's behaviour).

Castle (2007) argued that the selection of the most appropriate data model is dependent on the original format of the environmental data (e.g. image, CAD, shape file, etc.) and requirements put on agent-environment interaction. The concept of different data models have been demonstrated in Benenson and Torrens (2004) by discussing its implications on agent's neighbourhood. For instance, *Agent B* is considered a neighbour of an *Agent A* if it is located on a cell which shares an edge with the cell where Agent A stays (von Neumann neighbourhood). However, this could be seen as a characteristic of an agent rather than a quality of the environment.

Associating the decision of what environment type to implement with respect to the purpose of the geo-simulation model was not widely discussed. Nevertheless, the purpose of the model needs to be taken into consideration if the desired level of detail and quality of the generated outcomes should be achieved. For example, if the intention of the model is to provide a tool for evaluation of collision avoidance algorithms, the simulation space should contain high levels of detail that can capture obstacles of small sizes (e.g. lamp-post, bench, parked car, etc.). This would permit observation of the collision avoidance behaviour and collection of data at desired scale.

The effects of the environment with respect to changes of agent's movement (*sense of space and place*) were discussed by Crooks et al. (2008) and Castle (2007). They argued that the interaction with the environment should be specified with consideration of the dynamics occurring in the real system e.g. movement of evacuating pedestrians. This once again stresses the importance of utilisation of real-life system specific data when defining agent's behaviour. Although Benenson and Torrens (2004) specified that the set of migration rules that define agent's movement is a key component of a spatially aware agent, no further guidelines on how these rules should be defined, nor what are the variables which the rules need to include (e.g. speed, navigation preference, etc.) is provided. This aspect have been further discussed by Castle (2007) who associated human movement with its speed and direction.

2.3.1.4 Reasoning Process

The reasoning process refers to an algorithm that represents the decision making process by which the agent selects the most appropriate behaviour in a given situation (Bryson, 2004). The different methods which can be used to define the agent's reasoning process have only been discussed by Castle (2007). He classified them into five categories according to the amount of information an agent uses as an input for the decision making, and the complexity of the process. He did not specify advantages of one reasoning process over another, their limitations, nor discussed for what type of models each of them is the most appropriate. Moreover, the list did not include references to existing models allowing reader to search for additional information if needed.

Two of the remaining publications (Benenson and Torrens, 2004 and Axelrod, 2007) limited the reasoning process of an agent to purely rule-based systems where the transition between two different behaviours are characterised by an explicit set of rules. Therefore, the only concerns of the authors were related to: (i) selection of the most appropriate programming language which is capable of representing such transitions (Axelrod, 2007), (ii) number of the rules and their complexity (Benenson and Torrens, 2004), and (iii) the amount of information needed to trigger the change between one behavioural state to another (Benenson and Torrens, 2004).

2.3.1.5 Results Analysis & Model Evaluation

The last aspect category considers selection of methods and processes by which the data generated by the simulation can be analysed. In addition this aspect also concentrates on determining how the implemented model can be assessed to identify its reliability with respect to the system it represents.

Axelrod (2007) and Zarboutis and Marmaras (2007) argued that data generated by simulation are in comparison to data collected by experimental studies clean of any ambiguities and don't possess any missing variables. This is mainly due to the fact that they are artificially created. This also enables the model developer to specify exactly what data need to be recorded (e.g. locations of the agents, value of agent's attributes, etc.) and how often. Therefore, before the model is developed questions and hypotheses which are asked on the collected data should be specified. The form of these questions also influence selection of the most appropriate analytical technique.

Axelrod (2007) argued that qualitative approach is the most appropriate for analysis of the generated data since the results are sensitive to the generalisation of the real-life system. He suggested that the findings should be discussed in a narrative form with respect to the purpose of the model. In contrast Zarboutis and Marmaras (2007) concentrated on application of quantitative analytical methods. However, they concluded that use of statistics may not be necessarily appropriate because the correctness of the model output is dependent on the model validity. Therefore, although statistical tests support a set of hypotheses about the emergence of the modelled phenomenon, there is no guarantee that the observed pattern is realistic.

Evaluation of the functionality and reliability of the developed model was, in comparison to other discussed aspects, approached in very similar way across four of the five publications (Axelrod, 2007; Castle, 2007; Zarboutis and Marmaras, 2007; Crooks et al., 2008). The main processes used for assessing quality and accuracy of the model with respect to the system it represents are:

- **Verification:** making sure that an implemented model corresponds with the design by testing each newly implemented module whether it behaves as expected (Crooks et al., 2008; Axelrod, 2007). Castle (2007) suggested that a user should always run several tests to gain a confidence in the model and to make sure that the model does what is required.

- **Validation:** evaluating to what degree the model matches the real-world situation it represents. Castle (2007) argued that validation does not only help to identify the capabilities of a simulation model but also facilitate discovery of its limitations.

- **Calibration:** fine-tuning the model to a particular context. According to Zarboutis and Marmaras (2007) calibration can be avoided if the exact values of the key model parameters are left to the user to specify. Such parameters could for instance be speed of the evacuees, number of agents or the time of the simulation. However, the quality of the results is then dependent on the level of user's knowledge about the modelled system.

Axelrod (2007) and Crooks et al. (2008) argued that the confidence in a model increases if more reports exist about its successful application. To pursue this, the model needs to be developed in such a way which would allow its re-use on similar but independent scenarios (e.g. possibility of importing plans of different buildings), or to enable replication of the generated results by somebody who would implement the model from scratch.

2.3.1.6 Evaluation of Proposed Guidelines

Only Castle (2007) covered the whole spectrum of the considerations. However, the provided guidelines were created with intention of assessing existing pedestrian evacuation models. Therefore their application on development of a new model is not appropriate. Beside, the assessment process was not specified purely for agent-based models but also other simulation approaches (e.g. aggregate models). Moreover, the understanding of the application domain is only restricted to technical demands on the model, its cost and accessibility.

Axelrod (2007) emphasised several important issues related to the clarity of the simulation output and quality of the model itself. However, he did not provide any guidelines on how to design the model and what to consider when defining its components. Therefore, although very helpful, this publication can also not be taken as a single source of information or advice on developing a geosimulation model for disaster management.

Framework proposed by Benenson and Torrens (2004) contains a definition of model components at a very high level of abstraction. Therefore, the developer would still need to search additional information sources to adopt the general approach to disaster management. Beside, their framework does not include any considerations related to understanding of the application domain nor results analysis and model evaluation. These are however crucial to determine credibility of the model with respect to its purpose and possible application.

A detail methodological framework specifically tailored for the needs of disaster management was discussed in Zarboutis and Marmaras (2007). Nevertheless, the publication contains very specific guidelines only limited to the system modelled. Hence, the considerations are mostly related to identification of technological elements of the system and steps security operator in an underground railway system should undertake during a fire (e.g. adjusting ventilation, emergency lighting, sprinklers, emergency exits, etc.). The considerations related to understanding of human behaviour and importance of recognising how people reason about the enclosure in which they are trapped were not incorporated and discussed.

Crooks et al. (2008) extended the considerations presented by Axelrod (2007) also to those which are related to earlier stages of the development process preceding the implementation phase. Although the identified challenges are widely discussed, they do not cover the whole spectrum of the summarised considerations (Table 2.5).

To identify usability of the proposed frameworks all authors provided evidence of their evaluation by assessing already existing models (Benenson and Torrens, 2004; Castle, 2007) or by implementing a prototype by which practical implementations of the guidelines and considerations were illustrated (Benenson and Torrens, 2004; Castle, 2007; Crooks et al., 2008; Zarboutis and Marmaras, 2007; Axelrod, 2007).

2.3.2 Assessment of the Geo-simulation Models With Respect to the Identified Aspects

The preceding discussion led into organisation of considerations related to development of disaster management related models into five aspects. It was identified that each aspect is associated with a large range of often diverse issues and challenges. These are summarised in following key questions which form a new set of criteria against which the 35 reviewed simulation models are once again evaluated. The key aim of the evaluation is to identify how the researchers dealt with the challenges and considerations listed. In addition, this evaluation also reveals what are the most common problems during the model development and to what extent the identified considerations have been addressed and with what success.

Understanding of the Application Domain (further discussed in Section 2.3.2.1)

Q1: Has initial investigation regarding understanding of the basic properties of the modelled system been conducted?

Q2: Have the system related problems and issues with respect to disaster management been identified?

Q3: Have the potential users of the model been consulted to specify their requirements of the model?

Human Behaviour Representation & Parameterisation (further discussed in Section 2.3.2.2)

Q1: Has the behaviour of the agents been specified with respect to the behaviour of the real system entities the agents represent?

Q2: Does the research reference the source which was consulted for definition of the agent's behaviour?

Q3: Has any additional research been conducted to obtain more information regarding the behaviour of the agents?

Q4: Does the parameterisation of the model correspond with the characteristics of the modelled system?

Q5: Do the attributes of the agents correspond with the entities they represent?

Environment Representation & Sense of Space and Place (further discussed in Section 2.3.2.3)

Q1: What format is used for the representation of the environment?

Q2: Has the selection of the specific environmental representation been sufficiently justified and properly explained?

Q3: Does the environment represent a real location? If yes, is the representation accurate for the selected scale of the geo-simulation?

Q4: Has the agent interaction with the environment been clearly specified?

Q5: Has the agent interaction with the environment been based on behaviour observed in the real-life system and the source of information properly referenced?

Reasoning Process (further discussed in Section 2.3.2.4)

Q1: What action selection technique has been used to represent the agent's reasoning process?

Q2: Has the selected approach been adequately explained?

Q3: Has the selected approach been justified?

Results Analysis & Model Evaluation (further discussed in Section 2.3.2.5)

Q1: Have the results of the geo-simulation been analysed with respect to the purpose of the model?

Q2: Has the adopted analytical approach been justified and adequately explained?

Q3: Does the research discuss the model's contribution and limitations?

Q4: Has the model been properly validated, verified and calibrated?

Table 2.6 summarises the reviewed models with respect to the above synopsis. The table headings represent the aspects and the sub-headings correspond to the order of the questions. The key of abbreviated terms used in the table is provided in Table 2.7.

Table 2.6: Organisation of the reviewed models according to the identified considerations.

Key reference	UAD			HBRP					ERSPS					RP			RAME			
	Q1	Q2	Q3	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q1	Q2	Q3	Q4
Adams et al. (2008)	N	N	N	N	OM	N	PART	N	HYB	N	Y	N	N	OTH	REF	Y	N	N	N	N
Banarjee et al. (2005)	N	N	N	N	N	N	N	N	SNET	N	N	N	N	ACO; FL	Y	Y	N	N	N	N
Batty et al. (2003)	NFWR	NR	Y	Y	Y	SUR; AN	HIS	NP	RL	N	Y	Y	Y	ACO	Y	Y	Y	Y	Y	VA, VE, CA
Braun et al. (2005)	N	N	N	OM	OM	OBS	DR	SIMP	HYB	Y	Y	OM	NCS	FSM; FFM	Y	N	Y	Y	Y	VA
Buford et al. (2006)	NFNR	N	N	N	N	N	NCS	SIMP	CYS	Y	N/A	N/A	N/A	BDI	Y	Y	N	N	N	N
Carley et al. (2006)	NFNR	N	N	Y	LIT	N	HIS	CEN	SNET	Y	Y	N/A	N/A	FSM	Y	N	Y	Y	Y	VA; CA
Castle (2007)	NFWR	WR	Y	Y	LIT; Y	OBS; SUR; AN	DR; HIS	HIS	RL	Y	Y	Y	Y	RBS	Y	N	Y	Y	Y	VA; VE; CA
El Rhalibi and Taleb-Bendiab (2006)	N	N	N	N	N	N	N	N	3D	N	N	N	N	FSM	Y	N	N	N	N	N
Eubank et al. (2004)	N	WR	N	N	N	N	PART	CEN	HYB	Y	Y	N	N	NCS	N	N	Y	Y	N	N
Farinelli et al. (2003)	N	N	Y	N	OM	N	PART	N	HYB	N	N	N	N	OTH	Y	N	Y	Y	Y	N
Farinelli et al. (2004)	NFNR	N	Y	N	OM	N	NCS	N	HYB	N	Y	N	N	NCS	N	N	N	Y	Y	N
Habibi et al. (2002)	N	N	N	N	OM	N	PART	N	HYB	N	Y	Y	N	OTH	N	N	Y	Y	Y	N
Helbing et al. (2000)	N	N	N	Y	LIT	N	NCS	SIMP	NCS	N	N	N	N	FFM	Y	N	N	Y	N	CA
Henein and White (2007)	N	N	N	N	N	N	N	N	RL	N	N	Y	N	FFM; ACO	Y	Y	Y	Y	Y	VA
Hu (2006)	N	N	N	N	N	N	N	N	NCS	N	NCS	Y	N	FSM	Y	N	N	N	N	N
Kitano et al. (1999), Takahashi et al. (2002) and Takahashi (2006)	NFNR	N	N	Y	N	N	PART	N	HYB	N	Y	N	N	NCS	REF	Y	Y	Y	N	N
Kleiner et al. (2006)	N	N	N	N/A	N/A	N/A	N/A	N/A	HYB	Y	Y	N/A	N/A	OTH	Y	N	Y	N/A	Y	VA
Murakami et al. (2002)	N	N	N	Y	Y	AN	DR	HIS	HYB	N	NCS	Y	Y	RBS	Y	Y	Y	Y	Y	VA
Musse et al. (2007)	N	N	N	Y	Y	N	HIS	N	3D	N	Y	Y	Y	OTH	Y	N	Y	Y	Y	N
Mysore et al. (2005)	N	N	N	Y	N	N	NCS	NCS	NCS	N	NCS	N	N	RBS	N	N	N	Y	N	N
Mysore et al. (2006)	N	NR	N	N	N	N	N	N	GNET	Y	Y	N	N	RBS	N	Y	N	Y	N	N
Pan et al. (2007)	N	N	N	N	N	N	N	N	HYB	N	N	Y	N	RBS; FFM	Y	OS	Y	Y	Y	N

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Key reference	UAD			HBRP					ERSPS					RP			RAME			
	Q1	Q2	Q3	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q1	Q2	Q3	Q4
Rahmandad and Sterman (2008)	N	N	N	OM	OM	N	HIS	N	SNET	Y	N	N/A	N	FSM; FFM	Y	Y	Y	Y	Y	VA
Raupp-Musse and Thalmann (2001)	N	N	N	N	N	N	N	N	3D	N	N	N	N	OTH	Y	N	N	N	N	N
Raymond and Reed (2006)	N	N	N	N	N	N	PART	N	HYB	N	Y	N	N	OTH	Y	N	Y	Y	Y	N
Reinaldo et al. (2005)	N	N	N	N	N	N	PART	N	HYB	N	Y	N	N	OTH	Y	OS	N	N	N	N
Roche et al. (2008)	N	N	N	Y	LIT	N	NCS	NCS	NCS	N	NCS	Y	N	NCS	N	N	N	N	N	N
Schurr et al. (2005)	N	N	N	N	N	N	N	N	NCS	N	N	N	N	OTH	N	Y	Y	N	N	N
Shendarkar et al. (2006)	N	N	N	N	Y	OTH	N	NCS	GNET	Y	Y	N	N	BDI	N	N	N	N	N	N
Still (2000)	NFWR	WR	Y	Y	Y	VID; OBS; PHO; AN	HIS	SIMP	3D	N	Y	Y	Y	FFM	Y	Y	Y	Y	Y	VA; VE; CA
Ulicny and Thalmann (2002)	N	N	N	N	N	N	N	N	3D	Y	Y	Y	N	FSM	Y	N	N	N	N	N
Visser et al. (2004)	N	N	N	N	N	N	PART	N	HYB	N	Y	N	N	NCS	N	N	Y	N	N	N
Wagner et al. (2003)	NFWR	WR	Y	Y	Y	AN	HIS	HIS	CYS	N	N/A	N/A	N/A	OTH	Y	N	N	N	Y	VA
Wickler et al. (2006)	NFWR	WR	Y	Y	Y	N	NCS	NCS	CYS	N	N/A	N/A	N/A	OTH	Y	Y	Y	Y	Y	N
Zarboutis and Marmaras (2007)	FWR	N	Y	Y	Y	AN; OBS	PART	SIMP	RL	N	NCS	N	N	RBS	N	N	Y	Y	Y	N

Table 2.7: Key of abbreviate terms used in Table 2.6

Abbreviation	Description
UAD	Understanding of the Application Domain
HBRP	Human Behaviour Representation & Parameterisation
ERSPS	Environment Representation & Sense of Space and Place
RP	Reasoning Process
RAME	Results Analysis & Model Evaluation

Consideration	Question	Abbreviation	Description
UAD	Q1	NFWR	Description of the system is provided but not in any formal way; provision of references to the information sources
		NFNR	Description of the system is provided but not in any formal way; no reference was provided regarding the source from which this information was extracted
		FWR	The system was described with use of formal technique; provision of references to the information sources
		N	This question was not considered
	Q2	WR	Problems, issues and challenges connected with the system have been identified; reference to the information sources was provided
		NR	Problems, issues and challenges connected with the system have been identified; no reference was provided regarding the source from which this information was extracted
		N	This question was not considered
	Q3	Y	Yes, potential users of the model have been consulted
		N	No, potential users of the model have not been consulted
HBRP	Q1	Y	Yes, the behaviour of agents has been specified with respect to behaviour of the real system entities
		OM	The behaviour corresponds with the behaviour defined in the original model
		N	No, the behaviour of agents has not been specified with respect to behaviour of the real system entities
		N/A	Not applicable for this type of model
	Q2	Y	Yes, reference to the source of information is provided
		N	No, no reference was provided regarding the source from which this information was extracted
		OM	Based on specification used in other model
		LIT	Related literature was reviewed
		N/A	Not applicable for this type of model
	Q3	SUR	Additional surveys were conducted

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Consideration	Question	Abbreviation	Description
		OBS	Additional observations of the system were conducted
		VID	Video footage capturing the modelled situation was taken
		PHO	Photographs capturing the modelled situation were taken
		AN	Additional analysis of historical records, photographs, video footage, etc. were conducted
		OTH	Other sources
		N/A	Not applicable for this type of model
		N	This question was not considered
	Q4	HIS	Yes, based on historical data
		Y	Yes, the model has been parameterised to correspond with the real situation
		PART	Yes, the model has been parameterised to correspond with the real situation but only partly
		DR	Yes, based on evacuation drills or response exercises
		NCS	Information regarding this question is not clearly specified
		N/A	Not applicable for this type of model
		N	This question was not considered
	Q5	SIMP	The attributes are omitted due to the scale of the simulation
		CEN	Census data were used
		HIS	Historic information was used
		NCS	Information regarding this question is not clearly specified
		N/A	Not applicable for this type of model
		NP	Not possible due to the nature of the system
		N	This question was not considered
ERSPS	Q1	RL	Regular lattice
		GNET	Geographic network
		SNET	Social network
		3D	Three-dimensional space
		CYS	Cyberspace
		HYB	Hybrid
		NCS	Information regarding this question is not clearly specified
	Q2	Y	Yes, the selection was sufficiently justified or properly explained
		N	No, the selection was not sufficiently justified nor properly explained
	Q3	Y	Yes, the environment represents a real geographic location
		N	No, the environment does not represent any real geographic location

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Consideration	Question	Abbreviation	Description
		NCS	Information regarding this question is not clearly specified
		N/A	Not applicable for this type of model
	Q4	Y	Yes, the interaction between agent and the environment is clearly specified
		OM	the interaction is identical with the interaction specified in the original model which is properly referenced
		N/A	Not applicable for this type of model
		N	This question was not considered
	Q5	Y	Yes, the interaction between an agent and the environment is based on behaviour observed in real-life system and the source of this information has been properly referenced
		NCS	Information regarding this question is not clearly specified
		N	No, the interaction between agent and the environment is not based on behaviour observed in real-life system
		N/A	Not applicable for this type of model
RP	Q1	ACO	Ant colony optimisation
		FL	Fuzzy logic
		FSM	Finite state machine
		FFM	Force field model
		RBS	Rule-based system
		BDI	Beliefs, desires and intentions architecture
		OTH	Other type of reasoning process
		NCS	Information regarding this question is not clearly specified
	Q2	Y	Yes, the selected approach was properly explained
		REF	The selected approach was not explained but reference to other publication with more information was provided
		N	The selected approach was not clearly explained
	Q3	Y	Yes, the selected approach was justified
		N	No, the selected approach was not justified
		OS	The selected approach was compared with other simulation technologies
RAME	Q1	Y	Yes, the results were analysed with respect to the purpose of the model
		N	No, the results were not analysed with respect to the purpose of the model
	Q2	Y	Yes, the selected analytical approach was justified and clearly explained
		N	No, the analytical approach was not described or justified

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Consideration	Question	Abbreviation	Description
		N/A	Not applicable for this type of model
	Q3	Y	Yes, the article specifies model's contribution and its limitations
		N	No, the article does not specify model's contribution and its limitations
	Q4	VA	Model was validated
		VE	Model was verified
		CA	Model was calibrated
		N	No information regarding evaluation of the developed model is provided

2.3.2.1 Understanding the Application Domain

The answers to the three questions which depict the key issues related to understanding of the application domain are summarised in Figure 2.2. The bar chart in image a) indicates that in 71 % of the reviewed models such research was not conducted. This clearly shows that collecting information about the functionality of the system and description of its key components have not been regarded as one of the crucial parts of the model development process. This signifies that the majority of the reviewed models are based on often simplified assumptions of the researchers about the characteristics of the system. In addition, the publications also lack any provision of justification regarding the system definition as it is depicted in the geo-simulation model.

In the remaining articles quality and quantity of system relevant information significantly differs. Although 11 % of the publications provided a succinct description of the application domain, the source from which this information was obtained was not referenced. Therefore, it is impossible to indicate how reliable the model is with respect to its representation of the system under investigation.

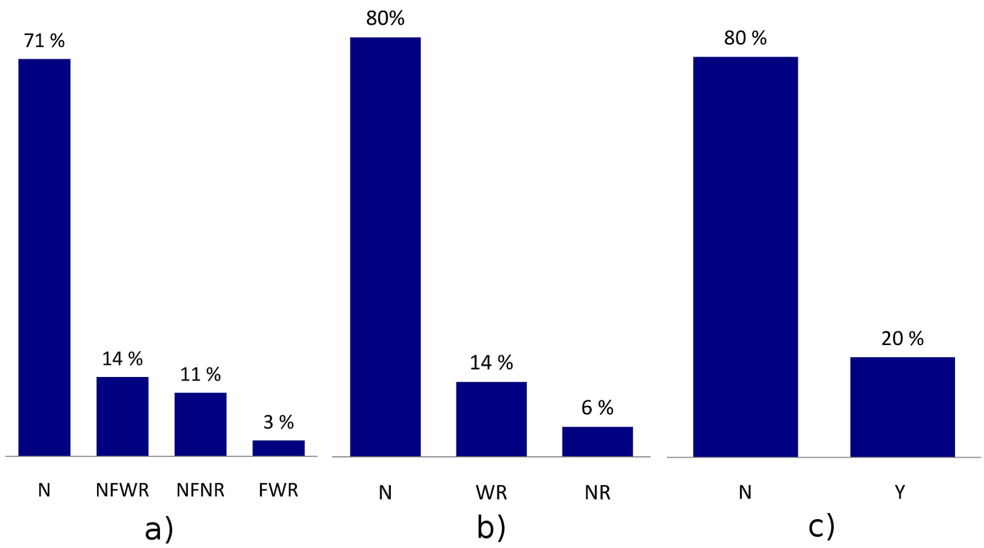

Figure 2.2: Summary of understanding of the application domain related questions.

14 % of the articles provide reference to sources from which such information was extracted. The main source of such information were direct discussions with the response personnel (Still, 2000; Wagner et al., 2003; Batty et al., 2003) and relevant authorities (e.g. Carnival Review Group; Batty et al., 2003, King's Cross Advisory Panel; Castle, 2007, Wembley stadium staff and management; Still, 2000). Nevertheless, the information regarding the characteristics of the system was not collected in any formalised way but as a summary in linear textual description.

Only one publication (Zarboutis and Marmaras, 2007) reported an application of a formal method to capture and understand the processes and components of the modelled system (hierarchical task analysis). This technique is limited to collection of the process related information which is reported in a form of activities. Concerns of people involved in the system and their relationships are not considered. These however play an important role in the functionality of the system since they are the main driving force for implementing the system related activities.

Considerations related to application of the developed model into real-life incident response operations were mainly discussed by the researchers who collected information about the real-life system by direct contact with the domain experts. This information is summarised by bar chart c) in Figure 2.2 which indicates that such intention was in 20 % of the models not considered.

Bar chart b) indicates that 80 % of the reviewed publications did not reference any system related problems or issues that the geo-simulation model could help to resolve. Such considerations were also omitted in some of the articles where collection of system related information was discussed (Buford et al., 2006; Carley et al., 2006; Zarboutis and Marmaras, 2007). This indicates that understanding the application domain is mostly focused on a bold description of the system without searching for any deeper meaning why the system operates in that particular way and what problems it faces.

2.3.2.2 Human Behaviour Representation & Parameterisation

The need for realistic representation of the interacting agents has been recognised by 37 % of the reviewed models (Figure 2.3 a)). In 54 % of the models the interaction of the agents was based purely on the researchers' assumptions on how people would react in the situations represented by the model. Braun et al. (2005) and Rahmandad and Sterman (2008) extended already existing models of additional components. Although they provide reference to the publication that describes the original model, they didn't clearly specify whether the behaviour of the agents in the improved model is more realistic or not.

Bar chart b) in Figure 2.3 illustrates what sources of information have been consulted when defining the agents' behaviour. Since some of the publications referenced more than one information source the count totals more than 100 %. Since this type of classification is also done in several subsequent questions different colour is used to distinguish them from those where the categories are mutually exclusive (e.g. bar chart a)).

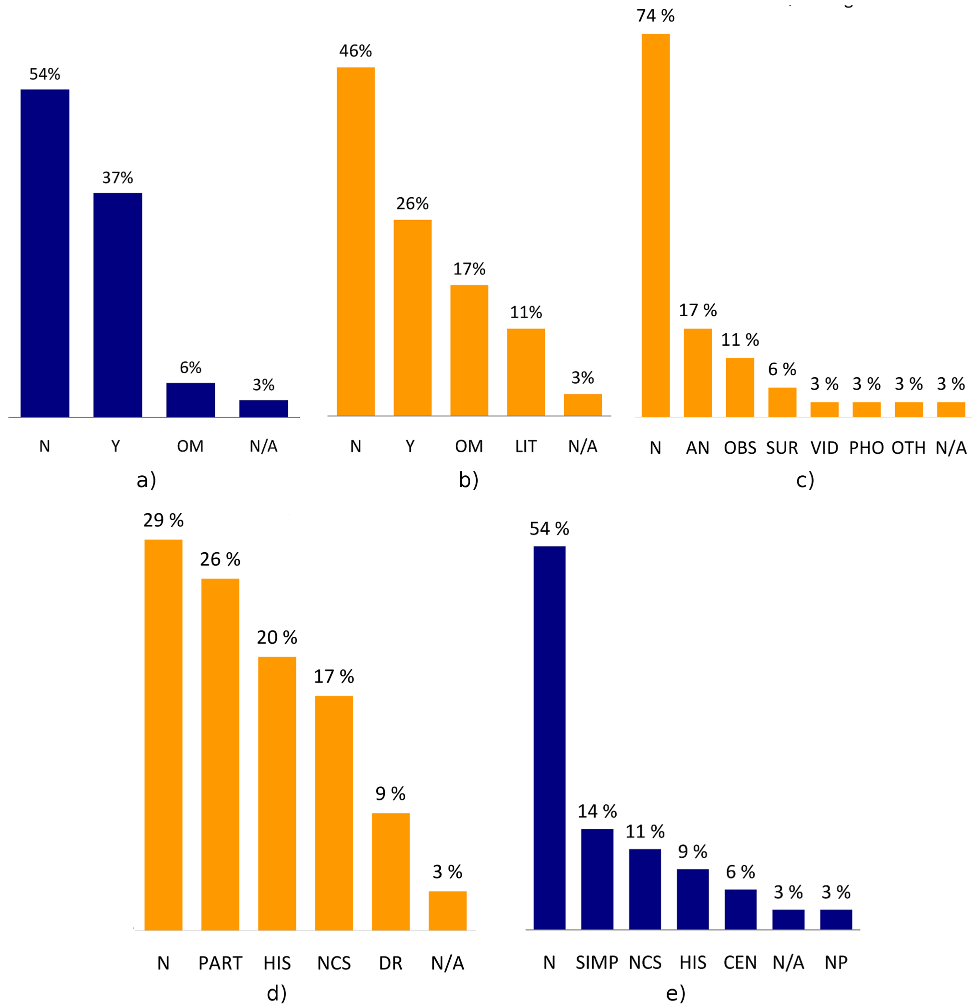

Figure 2.3: Summary of human behaviour representation & parameterisation related questions.

Referring back to the bar chart b) (Figure 2.3) 46 % of the publications did not contain any reference to the sources which were consulted when defining agent's behaviour. The behaviour was based in 11 % of models on findings from scientific literature. For instance Castle (2007) and Helbing et al. (2000) reviewed psychology and sociology publications related to behaviour of pedestrians during evacuation from enclosed spaces, Carley et al. (2006) and Roche et al. (2008) consulted epidemiology articles to identify how a disease or a biological terrorist attack spreads or propagates through a city in specific time interval. In 26 % of the publications additional research was conducted to obtain the necessary information which is specifically related to the scenario the model represents. The different research approaches are summarised in histogram c) (Figure 2.3).

20 % of the publications conducted additional analysis of empirical data collected by others to extract information which was not considered in the original work. For instance Batty et al. (2003), Castle (2007) and Still (2000) analysed photographs or CCTV footage to detect behaviour patterns of crowding pedestrians, Zarboutis and Marmaras (2007) consulted standard operating procedures of metro personnel to depict how individual response tasks are allocated and in what sequence. 11 % of the researchers conducted observation of the system (Castle, 2007; Still, 2000; Zarboutis and Marmaras, 2007). However, these were only made during non-emergency situations. In contrast to many of the reviewed publications, Murakami et al. (2002) described how the behavioural rules were formed. This is very valuable information since the user of the model can judge whether the behaviour is sufficiently represented for the desired purpose or not.

Shendarkar et al. (2006) used experiments in CAVE (virtual reality environment) to capture human response to an explosion. Since virtual reality can simulate dangerous environments this provided an unique opportunity to collect information that is normally very challenging and often not possible to obtain. However, the publication does not mention how successful such experiment was, how many times it was tested, and how the obtained information was incorporated into the agent-based model. The emergency situation was also simulated by Braun et al. (2005) who organised a fire drill at the university to record students' behaviour during the building evacuation.

Bar chart d) indicates that in 29 % the settings of the model's parameters were done without an intention to resemble realistic scenarios. In another 14 % of publications it was not clearly specified on what information the model was parameterised. This means that outputs generated by 43 % of the reviewed models are unreliable with respect to disaster management because they don't represent the simulated incident in any authentic way. This problem was partially overcome by 29 % of the researchers. However, the parameterisation corresponds with the real-life situation only partially since information for some of the parameters was not available. For instance in RoboCup Rescue (Farinelli et al., 2003; Habibi et al., 2002; Kitano et al., 1999; Takahashi et al., 2002; Takahashi, 2006; Rahmandad and Sterman, 2008; Reinaldo et al., 2005; Visser et al., 2004) the real-life information was only used for parameterisation of the model's initial state (e.g. number of collapsed buildings, trapped people, etc.). Historical data of past disasters were used by 20 % of the reviewed models to determine number of agents and their distribution on the simulation space (e.g. medical records; Carley et al., 2006; Rahmandad and Sterman, 2008, post disaster briefing reports Wagner et al., 2003). However, such information does not always exist. Therefore, Castle (2007), Braun et al. (2005), and Murakami et al. (2002) used data collected during evacuation drills.

Bar chart e) indicates that in 54 % the parameters forming agent's characteristics have been selected solely based on assumptions of the developers. Axelrod (2007) pointed out that capturing human personality into a set of artificially created parameters is very challenging. Therefore, only several, which the researchers believe have the most impact on the final response, are usually defined. For example Mysore et al. (2006) characterised each agent by *perceived level of distress*, *degree of worry*, and *agent's current health level*. However, it is often the case that no reasons are provided why these parameters were prioritised over other human characteristics.

2.3.2.3 Environment Representation & Sense of Place and Space

The definition of the format in which the simulation space is represented has not been identified in 14 % of the reviewed models (bar chart a) Figure 2.4). The remaining models can be categorised according to the used data type into five groups:

- **Network** depicted as a bi-directional graph representing connection between two or more geographical locations (geographical network representing roads; e.g. Mysore et al., 2006; Shendarkar et al., 2006) or social relations between individual agents (social network; Banarjee et al., 2005; Carley et al., 2006; Rahmandad and Sterman, 2008).

- **Regular lattice** which can take different forms and sizes. For instance, Castle (2007) and Still (2000) defined a cell as an area just big enough to accommodate one agent of average person size (0.4 m x 0.4 m or 0.5 m x 0.5 m). Their simulation space represented several stories of an underground station or a stadium. A cell can also depict larger areas; Batty et al. (2003) represented the Notting Hill carnival route by regular lattice of 7 m x 7 m cell size.

- **Cyberspace** representing different locations in a computer system, Internet or sensor networks. This data type forms a graph where the locations are depicted as nodes and the information or data flow is represented by the edges. Such representation is used for simulation of task allocation (e.g. Wagner et al., 2003) or for connection and data fusion between several simulators (e.g. Buford et al., 2006).

- **Hybrid** consists of combination of two or more of the above listed data type representations. Use of hybrid data model is connected with RoboCup Rescue-based models where each simulator depicts the simulation space in different format. The original platform is capable of changing the representation between 2D and 3D (Kitano et al., 1999; Takahashi et al., 2002;

Takahashi, 2006) of high resolution to enable closer exploration of the rescue operation. This was further extended to sensor networks (weather Adams et al., 2008, or GPS locations of the first responders Kleiner et al., 2006) to include up-to-date information from the incident site.

- **3D space:** where the objects represented in the simulation space as well as agents have 3D form. Such representation was mostly implemented in models that were developed for gaming and film industry (El Rhalibi and Taleb-Bendiab, 2006; Raupp-Musse and Thalmann, 2001; Musse et al., 2007; Ulicny and Thalmann, 2002).

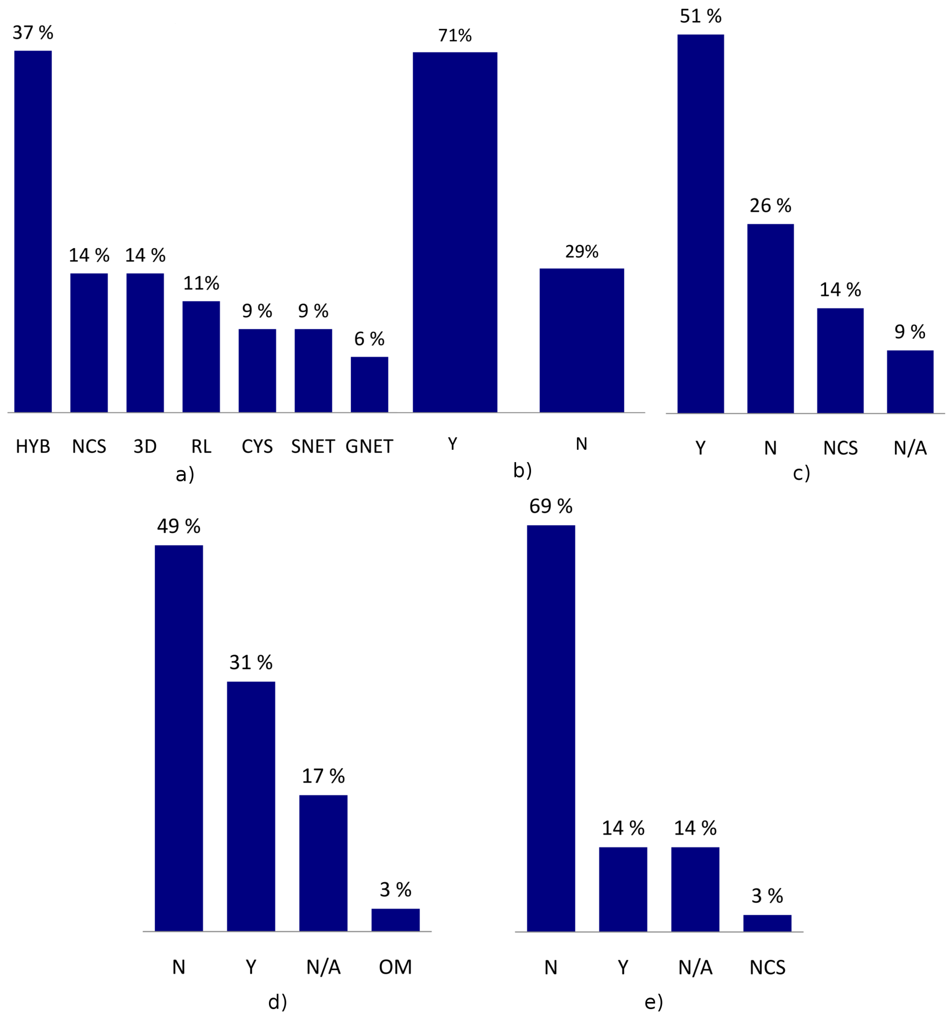

Figure 2.4: Summary of environment representation & sense of place and space related questions.

Bar chart b) indicates that in 71 % of the models the selected data type was not sufficiently justified or properly explained. This shows that although some of the publications contain information regarding the environment representation, they don't clearly explain how the simulation space was defined i.e, scale or resolution (if appropriate), size of the area, origin of the data, etc. The scale or resolution of the environment is particularly important since it is directly connected with the movement of the agent depicting distance between two locations (e.g. *emergency exit is two cells away*). Knowledge of the extent of the area enables the user to assess the scale of the emerging crowd (e.g. Batty et al., 2003) or the size of the area that is affected by the incident (e.g. Mysore et al., 2005). Such information was only specified in Castle (2007), Braun et al. (2005), Mysore et al. (2006), and Shendarkar et al. (2006).

As the Figure 2.4 c) illustrates in 40 % of the models the simulation space is synthetic or is not clearly specified. This means that the model environment does not depict any real location. However, from the remaining models it is not always very clear what background data were used and why. For instance, Shendarkar et al. (2006) and Mysore et al. (2006) claimed that they used publicly available GIS data but they don't provide any information regarding the source or the format of the data. Without such information it is impossible to determine the accuracy of the simulation space. Such lack of information limits application of the models in real-life. Clear justification was for instance provided by Castle (2007) and Ulicny and Thalmann (2002). While the decision of the former was guided by the requirements of the used simulation platform (Repast) and his limited programming knowledge, the latter was determined by the needs of the model application (gaming).

Clear description and justification of agent's interaction with the environment is equally important as specification of agent's behaviour as it was discussed in Section 2.3.1.2. It has already been outlined in Section 2.2.2.1 that human movement is highly influenced by space and place in which we reside. Unfortunately only 31 % of the publications (Figure 2.4 d)) presented such information. For instance, in Habibi et al. (2002) the agent selects the most appropriate route by assessing state of the road network with respect to fallen debris. However, the paper does not specify according to what criteria this classification was made and how exactly the movement of the rescue vehicles was coordinated. These criteria are often very simplistic.

The spatial behaviour of agents in 14 % of the models was based on real-life data (bar chart e). For instance, Castle (2007) and Still (2000) based the agent's movement on information collected through observations of the areas under investigation, or Murakami et al. (2002) analysed video sequences captured by Sugiman and Misumi (1988). Batty et al. (2003) claimed that although they were able to obtain information regarding the spectators initial and final positions, i.e. point of entry and the location from which they observed the parade, the information regarding the selection of the path each visitor followed was impossible to collect. Such problem was partly overcome by Raupp-Musse and Thalmann (2001). The movement of the agents corresponds to the trajectories of pedestrians extracted from a video footage. Unfortunately, applicability of this approach is limited to areas that can be captured in a visual range of a single video recorder.

2.3.2.4 Reasoning Process

Different approaches to representation of the agent's reasoning that were applied in the assessed models are summarised in bar chart a) Figure 2.5. In 31 % the reasoning mechanism was designed and developed from scratch to demonstrate capabilities of the newly defined algorithm. Schurr et al. (2005), Shendarkar et al. (2006), and Wickler et al. (2006) argued that the commonly used architectures (e.g. rule-based system, finite state machine, etc.) lack mechanisms that can deal with human cognition during complex dynamic situations.

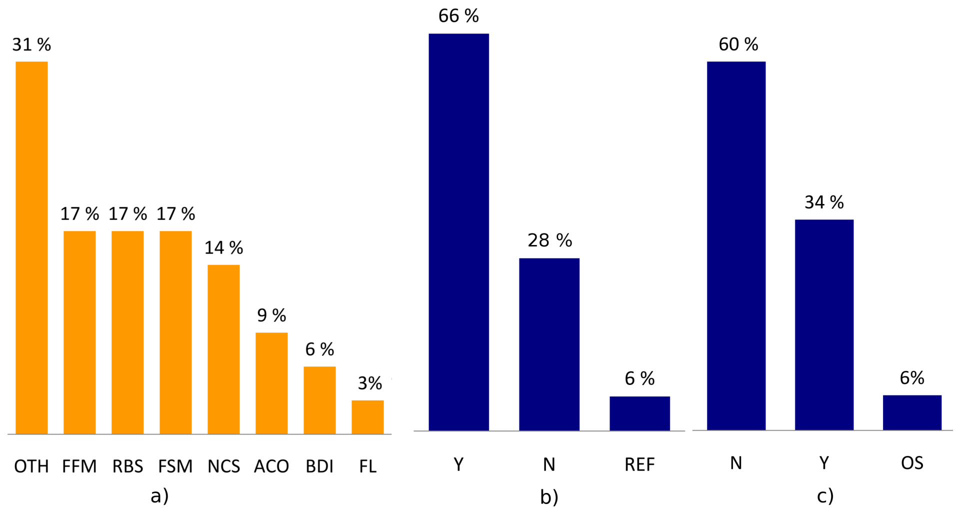

Figure 2.5: Summary of reasoning process related questions.

Rule-based system (RBS), finite state machines (FSM), and force field models (FFM) were used equally by 17 % of the publications. There is a clear distinction with respect to the background of the researchers and purpose of the geosimulation model; RBS were mostly selected by geographers (e.g. Castle, 2007) or social scientists (e.g. Murakami et al., 2002), FFM approach was adopted by computer scientists (Braun et al., 2005) or mathematicians (Still, 2000). This indicates that the former preferred approaches that can represent the processes in natural-like structure (e.g. *If* at the crossroad *then* turn right), the latter inclined towards application of physical laws (e.g. fluid dynamics) depicted by mathematical formulae. FSM was used by computer scientists (e.g. Hu, 2006; Ulicny and Thalmann, 2002) as well as researchers from other domains (e.g. Carley et al., 2006). Even though FSM are determined by set of rules, their structure is organised around the state of the agent rather than the environment as in RBS (e.g. *If* low energy *then* rest). Hence, this type of reasoning process was implemented in models where agents can reside in a finite number of states which are mutually exclusive (e.g. epidemiology: healthy, infected, dead, etc. Carley et al., 2006).

The remaining publications referenced systems that incorporated fuzzy logic (Banarjee et al., 2005), ant colony optimisation algorithms (Banarjee et al., 2005; Batty et al., 2003; Henein and White, 2007), of beliefs, desires, and intentions model (BDI; Buford et al., 2006; Shendarkar et al., 2006). In large numbers of these models such reasoning process was used mainly to test its capabilities. Hence the models were mostly developed as very simple prototypes without any concerns of depicting realistic agent's behaviour.

Bar chart b) indicates that in 66 % the selected architecture was properly explained. In addition, in another 6 % a reference to other sources with more information was provided. This emphasises the importance of such information when a model is developed for testing new state-of-the-art algorithms as was identified as the most common purpose of ABM in disaster management. However, justification of the selected approach was only provided in 34 % of the reviewed publications (bar chart c)). Hence, discussion related to evaluation of the implemented architecture and its comparison (even at conceptual level) with others was often missing.

2.3.2.5 Results Analysis & Model Evaluation

Bar chart a) (Figure 2.6) indicates that in 43 % of the publications the analysis of the results were not conducted in accordance with the original purpose of the model. Hence, no information was provided that concluded whether the implemented model successfully addressed the original research question. This lack of evidence hugely degrades the quality of the presented research. For instance, although Farinelli et al. (2004) specified that the aim of the research was to *"implement a tool to support decisions needed in a real-time rescue operation"*, the model was evaluated with respect to its robustness, i.e. how well the model architecture can cope with changing simulation parameters. It would be more relevant to obtain a feedback from real incident commanders regarding the model usability in real response operations.

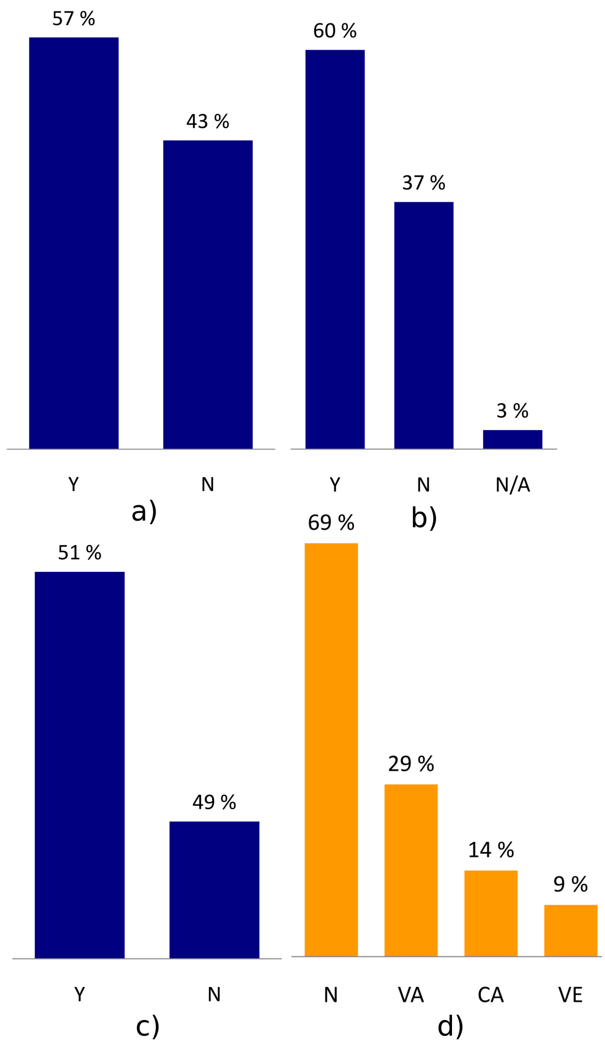

Figure 2.6: Summary of analysis & model evaluation related questions.

Bar chart b) demonstrates that in 60 % of the publications analytical techniques selected for the result evaluation were properly explained and justified. Although evidence on evaluation of the model regarding the original aim was missing, Farinelli et al. (2004) included a detailed description of evaluation criteria according to which the generated results were analysed. These were discussed with respect to the existing evaluation approach adopted by the RoboCup Rescue which Farinelli et al. found inappropriate for assessing performance of the modelled search and rescue operation. Nevertheless, the reasons for changing the evaluation process were based on the authors' own assumptions and were not defined or discussed with the domain experts to assess their relevance to evaluation of real-life response operation.

An essential part of the evaluation of geo-simulation model should be a discussion of the model contribution and its limitations. As the bar chart c) illustrates this was only a case in 51 % of the reviewed publications. For instance, although publications presenting RoboCup Rescue platform encouraged its use as a decision support tool for real-life rescue operations, the limitations regarding unrealistic and invalidated behaviour of the agents was not discussed. The description of limitations and contributions were mostly related to the technological improvements e.g. coupling with the sensor networks (e.g. Kleiner et al., 2006), or influence of the new agent type (e.g. *HelperCivilian*; Raymond and Reed, 2006).

Bar chart d) summarises how many of the reviewed models were evaluated through validation, verification, and calibration processes. It indicates that such assessment was in 69 % of the cases omitted. Critical evaluation of the model functionality is essential for determining the quality of its results (Crooks et al., 2008). Moreover, such information is also needed to assess the model capability with respect to its utilisation in real-life situations.

Validation was the most commonly applied evaluation process. Validation assesses to what degree the model matches the real-world situation it represents. Validation is crucial if the intention of the model is to predict emergence of a specific system under emergency conditions (Batty et al., 2003). Although prediction was the main purpose of models developed by Mysore et al. (2005, 2006) and Shendarkar et al. (2006), no comparison of the simulation results with the system under investigation was provided.

The process of calibration was only apparent from 14 % of the publication e.g. use of existing data on pedestrian flows (Helbing et al., 2000), or helicopter images of the previous years events (Batty et al., 2003). The majority of these papers also referenced validation and verification procedures. Since calibration is related to fine-tuning the model parameters to the simulated situation it can only be applied when sufficiently detailed data describing the real-life system exist (Crooks et al., 2008). An alternative approach to calibration is sensitivity analysis to determine to what extent the simulation results are affected by change of the model parameters (Sargent, 1999). Still (2000) determined by sensitivity analysis how local geometry (corridor width) influences speed of agents. Castle (2007) used sensitivity analysis to assess effects of altering passenger types (familiar and unfamiliar with the station) on total evacuation time.

Even though verification is an important part of the software development process only Batty et al. (2003), Castle (2007) and Still (2000) provided evidence of its realisation as a part of the model evaluation process. It is possible that verification was also conducted by others as an inseparable part of the development process (testing phase). Therefore, in these cases, the researchers might not have seen its separate documentation as important.

2.4 Bridging the Gaps

In order to obtain closer insight into the current state-of-the-art recently developed models capturing diverse systems within disaster management were reviewed from different perspectives. However, organisation of the models into tables of a structured form was not without problems. The aim of Table 2.2 was to assess what is the most common purpose and type of the models. In addition, it also contains information regarding the type of the model (e.g. evacuation, response coordination, etc.). The purpose categories were defined based on classification proposed in existing scientific literature. In contrast, the model type categories were generated implicitly with use of knowledge obtained from the publications. Allocation of the models into the model type categories was quite straightforward. Since many of the reviewed papers did not provide any clear specification of the model's purpose, it was not always very easy to identified what would be its appropriate utilisation. Hence, these models were mostly classified into the *Performance or optimisation* category since the authors often concentrated on improving technological aspects of this simulation approach.

Table 2.5 contains the key information that contributed towards definition of the five aspect categories that should be addressed during development of geo-simulation model for disaster management. The structure of this table was designed based on information collected from five peer-reviewed research publications discussing development of geo-simulation models of complex social systems (Axelrod, 2007; Benenson and Torrens, 2004) and disaster management in particular (Castle, 2007; Crooks et al., 2008; Zarboutis and Marmaras, 2007). As the table indicates, not all concerns were always considered. Each author used very different types of classification which was not necessarily in accordance with others. For the needs of the subsequent evaluation process, it was found essential to identify a common structure into which the presented frameworks and challenges could be re-classified. It is therefore possible that some statements might appear rather rigid. One such example is for instance approach of Axelrod (2007) to definition of (i) *Human Behaviour Representation & Parameterisation*, (ii) *Environment Representation & Sense of Place and Space*, and (iii) *Reasoning Process*. This publication only focused on problems related to implementation and evaluation of the final product, i.e. once the conceptual model is defined. Hence, the three aspects were only reviewed with respect to selection of the appropriate programming language which could represent the complex defined processes.

The aim of the last table (Table 2.6) was to evaluate how the aspects defined in the previous table were addressed during the development processes applied in the 35 reviewed models. It's complex structure of 735 cells (35 models and 21 columns) provided very organised detail insight into the uncounted problems. Each aspect was further explained by a set of more specific questions. This enabled identification of how the problems were resolved and whether the adopted approach was successful or not. Moreover, it also indicated what aspects have been prioritised over others and which were omitted during the development process and why. However, as in previous tables, the adopted review process was not precise since information related to the set of questions was at times missing.

2.4.1 Research Questions

Analysis of the scientific literature supported identification of the existing gaps in ABM research for disaster management by highlighting issues and problems development of such models faces. This was an essential first step towards improvement of the current state-of-the-art. These issues are summarised into a research agenda established with consideration of needs from both research perspectives: (i) the view of the model developer, and (ii) the perspective of experts in the disaster management. The research agenda is presented in a form of research questions organised into four categories:

- data related questions;
- operational questions;
- organisational questions;
- technical questions.

This classification adopts four out of eight categories that represent lessons GIScience community learned from the 9/11 terrorist attack summarised by Kevany (2005). The remaining four categories (general, customer, logistical, and special) were not considered because they don't correspond with the principles of ABM.

2.4.1.1 Data Related Questions

Questions in this category are related to collection and utilisation of real-life data and information for parameterisation of the geo-simulation model. In general, the model developers don't use real-life data for specifying the model intelligence in the design stage of the development process. Some researchers claimed that such data are not generally accessible and that additional research needs to be done in order to collect the information at the desired level of detail. Others don't consider this issue as important and populate the model according to assumptions they have about the modelled real-life system, or with simplified scenarios. The possible research questions related to utilisation of real-life data are:

1. How does the utility of geo-simulation models vary as a function of the quantity and precision of the real-life data?
2. What scientific techniques and methods can be used for collection of data regarding behaviour of the system entities which are represented by the interacting agents?
3. How can complex human behaviour be generalised into a simulation model?
4. What are the most appropriate ways of collecting information regarding interaction of people with the environment?
5. How can the extent of environmental effects on human behaviour be identified and measured?

2.4.1.2 Operational Questions

This category groups together questions that are associated with understanding the application domain for which the model is developed. The majority of the reviewed geo-simulation models focused on addressing computational issues related to the performance of the developed algorithms. Therefore, the main interest of the researchers was to test capabilities of the state-of-the-art technology. This approach however challenges potential application of the developed models to assist with addressing real-life problems. These issues are currently overcome by implementation of models that don't capture any realistic situations. The possible research questions are:

1. Would application of geo-simulation models in disaster management be more globally accepted if the model developers addressed domain specific needs?

2. How can domain knowledge (e.g. experience of response personnel) embedded in the real-life system be collected and used for implementation of geo-simulation models?

3. What strategies are required to support model developers with learning the generic principles of the modelled system?

4. What methods can be used for identification of the domain related problems and issues?

5. Can agent-based models facilitate work of experts in disaster management?

2.4.1.3 Organisational Questions

To date, no generally accepted framework which guides researchers through the geo-simulation model development process exists. The analysis of the research papers indicated that the current trend in ABM is oriented towards presentation of tangible results in the form of fully functional simulation models. However, not enough attention is given towards addressing issues and problems the researcher faces during development of the model. There is an apparent gap in implementation of generic principles and theories that would support creation of models that could be used for real-life problem solving. Currently, such issues are overcome by definition of very specific frameworks that are usually applied by a limited number or researchers often coming from the same institute. In addition, publications that concentrate on identification of key challenges don't provide any suggestions as to how these can be addressed. Questions emerging from these problems are:

1. Is it feasible to develop a generic framework that can provide clear guidelines to researchers that are developing geo-simulation models in disaster management?
2. What are the considerations that would need to be acknowledged in such generic framework?
3. How can the research community benefit from definition of strategies for assessing objectivity, quality, and reliability of the generic framework?
4. What are the domain specific requirements that need to be considered when developing a geo-simulation model for a particular purpose (prediction, training, experimentation, etc.)?
5. What are the domain specific requirements that need to be considered when developing a model of a particular type (e.g. evacuation, crowd behaviour, etc.)?
6. Can provision of clear specifications indicating what information needs to be published improve standard of scientific papers describing development of agent-based models for disaster management?

2.4.1.4 Technical Questions

There is an apparent trade off between the technical specifications of the geo-simulation model and considerations that have been discussed in previous categories of research questions. The literature review revealed that technical problems are only considered from the perspective of a software developer.

The problems and issues emerging from representation of complex human behaviour are often omitted. These issues are currently overcome by implementation of prototypes illustrating capabilities of the newly proposed algorithms without considering real-life situations. However, this does not indicate how the model would perform if it was populated with more realistic behaviours and complex environments. The questions emerging are:

1. What are the key considerations that need to be evaluated when developing agent's reasoning algorithm representing complex human decision making?
2. What are the criteria that need to be followed when parameterising model representing real-life system?
3. What preclude researchers in implementing realistic use case scenarios?
4. Does increase in complexity of the model architecture improve accuracy in representation of real-life systems?

Chapter 3

Methodology

3.1 Introduction

The previous chapter demonstrated the need for a large number of diverse research projects that could lead to improvement of the current state-of-the-art in ABM for disaster management. The analysis of the recently published research revealed that one of its main limitations is the lack of utilisation of real-life information when defining the behaviour of the agents and specifying representation of complex geographical environments. It was also identified that a large number of the models were developed as prototypes for testing performance of complex computational algorithms. This indicates that application of this simulation approach to solving real-life disaster related problems has often been neglected. With respect to these findings the research presented in the remainder of this thesis focuses towards addressing the following research question:

> **Can existing practical and conceptual issues that preclude utilisation of ABM in disaster management be partly resolved by enhancing the model development process to concentrate on identification and incorporation of real-life information?**

This chapter presents a methodology for a new model development process concentrating on characteristics and behaviour of the real-life system. This methodology is developed with consideration to the research agenda emerging from the literature review highlighting four potential directions for further research: *data related*, *operational*, *organisational* and *technical*.

With respect to *data related* issues specific attention is put on the collection and analysis of empirical data that represent behaviour of the modelled system. The *operational* part is addressed by presenting a method that is capable of providing an in-depth study of the currently adopted strategies and procedures to any specific incident. The third category (*organisational*) is the main focus of this research. The proposed methodology focuses on suggesting directions as to how some of the problems and issues that challenge utilisation of real-life information can be overcome. Finally, although resolving *technical* issues related to ABM is not the key interest of this research, challenges regarding generalisation of a complex real-life system into a geo-simulation model are discussed at the conceptual level.

The proposed methodology is defined in Section 3.2, which also contains discussion on its relevance with respect to the five aspects that guide development of geo-simulation models for disaster management defined in Section 2.3.1. Due to the diversity of the systems that can be represented, the methodology is intentionally kept in high level of abstraction in order to be universally applicable. Suggestions as to how the methodology can be implemented through definition of methods and techniques with focus to a specific system are presented in Section 3.3. These concrete methodological steps are formulated to support implementation of a new operational model (InSiM; *In*cident *Si*mulation *M*odel) that can simulate behaviour of people affected by a CBRN incident occurring in a city centre.

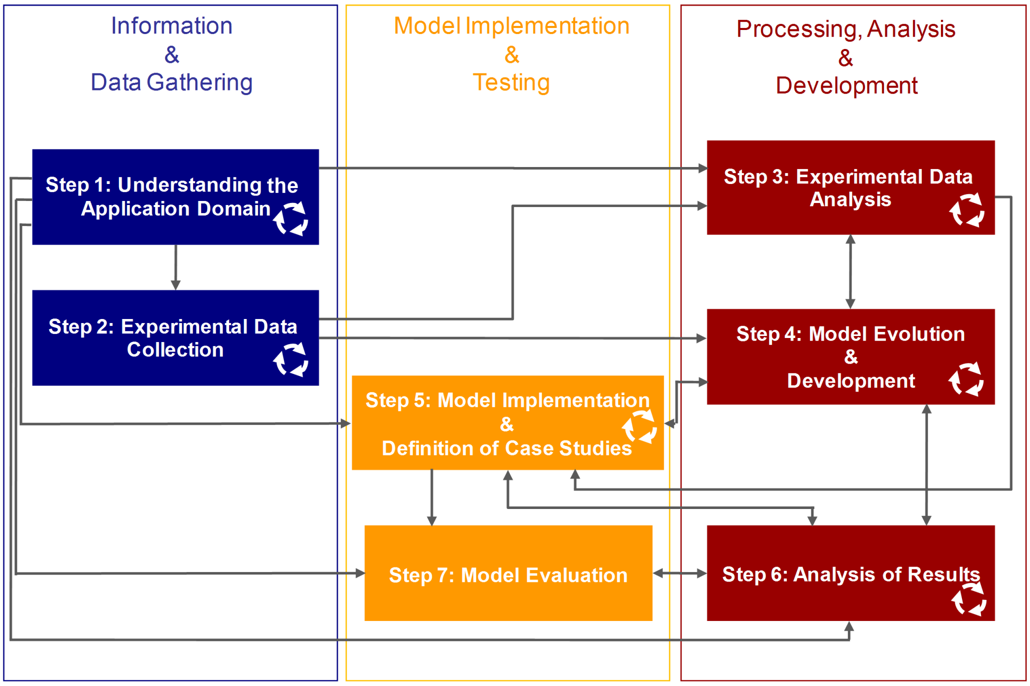

Figure 3.1: Methodology for development of a geo-simulation model for purposes of disaster management.

3.2 Defining the Methodology

The methodology proposed here consists of seven steps. These steps have been defined to accommodate all of the five model development aspects identified in the literature review. Table 3.1 illustrates in which methodological step each of these aspects should be addressed.

The methodological steps are organised into three categories based on their purpose within the development process and the type of output which they provide: (i) information & data gathering, (ii) model implementation & testing, and (iii) processing, analysis & development (Figure 3.1). The first category groups together steps that concentrate on collection of empirical data and information based on which the model can be defined. The focus of the second category is put on implementation of the model, assessing its reliability and testing its performance with respect to the specified requirements. Processes related to generalisation of the complex social system into a geo-simulation model are grouped into the last category. This category also includes analysis of the simulation generated outcomes.

The very tight connectivity and strong dependency between the steps is illustrated in Figure 3.1 by single or double-headed arrows. The double-headed arrow indicates that the connected steps need to be, at least partly, addressed simultaneously or in one or more iterations. Although their sequence during the development process is specified, due to their close connectivity these steps should be (at least at conceptual level) considered simultaneously. The highly iterative nature of the majority of the steps is depicted in the diagram by cycle arrows. This indicates that the corresponding processes and outcomes need to be re-visited and adapted to better fit the purpose of the model and to satisfy the desired level of accuracy and quality.

Each of the following paragraphs

- provides definition of the methodological step,
- highlights its expected outcomes, and
- discusses its relation with the specific aspects as depicted in Table 3.1.

Step 1: Understanding the Application Domain

This initial step focuses on gaining background understanding of the terminology and related processes of the specific disaster management system which could benefit from application of ABM. This is done by providing its description. In order to improve the system's functionality it is also important to identify what are the needs of the domain experts and what problems and issues the system currently faces. Based on the conducted analysis a decision can be made on how the real-life system can be depicted in the geo-simulation model, at which level of detail, and from which perspective it should be represented to be of an asset to the domain experts.

Methodological Steps	Understanding the Application Domain	Human Behaviour Representation & Parameterisation	Environment Representation & Parameterisation	Reasoning Process	Results Analysis & Model Evaluation
Step 1: Understanding the application domain	√		√		√
Step 2: Experimental data collection		√	√		
Step 3: Experimental data analysis	√	√	√		√
Step 4: Model evolution & development		√	√	√	√
Step 5: Model implementation & definition of case studies	√		√	√	
Step 6: Analysis of results	√				√
Step 7: Model evaluation	√	√	√	√	√

Table 3.1: Cross-referencing methodological steps with aspects highlighting needs of disaster management.

This step is mostly related to the *Understanding the Application Domain* aspect which was omitted in a large number of recently developed models omitted. It is also closely connected with *Environment Representation & Sense of Space and Place* since the simulation space needs to be defined with respect to the needs of the domain experts. Because the intention of the model is to provide information for decision making, the analysis of the simulation results needs to be defined in a way that could enable delivery of required information in the desired format (*Results Analysis & Model Evaluation*).

Step 2: Experimental Data Collection

Once the need for the model is identified the system should be further reviewed. This can be done by collecting more detailed information about its behaviour. Since disaster management systems are inherently connected with people (e.g. victims, response personnel, etc.) it is necessary to understand their behaviour and what information contributes to their decisions in the modelled situation. In this step appropriate procedures towards collecting data from which such information can be extracted are undertaken.

The the most significant aspect connected with this development step is *Human Behaviour Representation & Parameterisation* since the collected data form the basis for definition of the behaviour of the interacting agents. As real-life systems are embedded in geographical space the environment has inevitable effects on human behaviour. Hence, acquisition of data related to human-environment interaction is also an important part of this development step (*Environmental Representation & Sense of Place and Space* aspect).

Step 3: Experimental Data Analysis

The aim of this step is to select appropriate method(s) by which the collected empirical data can be analysed to identify common behavioural patterns that can be observed in a real-life system. Due to the high complexity of social systems, the analysis should be focused towards identification of system characteristics that are related to the specific purpose for which the model plans to be used by the domain experts.

This third step is related to the *Understanding the Application Domain* aspect, where the purpose and requirements of the model are specified. Since the analysis are conducted on data depicting human behaviour, this step is also associated with *Human Behaviour Representation & Parameterisation* and *Environment Representation & Sense of Space and Place* aspects which representing human response to the incident in the model. Assessment of accuracy and reliability of the simulation with respect to the system it represents is part of the model evaluation process (*Results Analysis & Model Evaluation* aspect). Therefore, the information emerging from the experimental data analysis can serve as means for validation of the agents' behaviour.

Step 4: Model Evolution & Development

The focus of this step is to develop a conceptual model which generalises the real-life system into parameters and algorithms that characterise the behaviour of the geo-simulation model. This is done by specifying and justifying a set of concepts which indicate the model scope and limitations.

The definition of the conceptual model is reflected by four aspects. Firstly, it determines the level of detail in which the human behaviour is represented. It also specifies the complexity of the parameters by which each agent is characterised (*Human Behaviour Representation & Parameterisation* aspect). Secondly, the synthetic simulation space and its effects on agent's behaviour should be defined with respect to the interactions observed in the real-life system (*Environment Representation & Sense of Space and Place* aspect). Thirdly, the conceptual model needs to specify the algorithm by which each agent selects the most appropriate reaction to a specific situation (*Reasoning Process*). Finally, at this stage the type, format, and frequency of data which are collected during the simulation need to be determined (*Results Analysis & Model Evaluation*).

Step 5: Model Implementation & Definition of Case Studies

The aim of this development step is to implement the geo-simulation model according to the specification provided in the conceptual model. Hence, presentation of a fully functional operational model is expected as the outcome. The functionality of the final model needs to be tested on a specific case study. This case study should represent a realistic scenario in which the model could be applied by domain experts during real emergency situation.

Since the case study needs to correspond with a situation that could occur in real life, it needs to be defined with respect to the knowledge obtained about the application domain and the specific emergency connected with the modelled system (*Understanding the Application Domain* aspect). Similarly, the simulation space needs to depict a geographic area that is realistic with respect to the type of emergency or process that is simulated. For instance, if the model represents evacuation during a football game, the simulation space should be defined with respect to the footprints of a real football stadium (*Environment Representation & Sense of Space and Place* aspect).

Step 6: Analysis of Results

This step focuses on identification of techniques and methods by which the data collected during a simulation run can be analysed. Subsequently, the selected approach is applied to obtain required information that could be further used by the domain experts during decision making processes related to the modelled system.

Therefore, this step needs to address problems and issues related to *Result Analysis & Model Evaluation* aspect. The selected analytical approach/es should correspond with the purpose of the model determined as part of the *Understanding the Application Domain* process.

Step 7: Model Evaluation

The aim of the last methodological step is to determine and apply an approach for evaluation of the implemented model with respect to its real-life utilisation in generating emergency-related information. In addition, any limitations of the model should be specified so domain experts can make accurate decisions as to the reliability and accuracy of the obtained findings.

The implemented model should be evaluated with respect to all the specified aspects. Regarding the *Understanding the Application Domain* the process needs to determine whether the original purpose was achieved (i.e, whether the model fulfills the requirements of the domain experts). The behaviour of the interacting agents needs to be validated with respect to the behaviour of the real-life system entities that the agents represent. This is related to the *Human Behaviour Representation & Parameterisation* aspect where the generalisation of the entities is determined. The use of data representing real geographic environments is connected with *Environmental Representation & Sense of Space and Place*. The evaluation process should also include reliability assessment of the defined decision making process of each agent (*Reasoning Process*). Finally, evaluation techniques should be defined with consideration to the questions asked in the *Result Analysis & Model Evaluation* aspect specified in the literature review.

3.3 Focusing Methodology for Development of InSiM

As was specified in Chapter 1 the disaster management process selected for investigation in this research identifies the appropriate locations of CBRN cordon zones. This section demonstrates how the methodology can be further extended to support development of an operational geo-simulation model that could facilitate decisions on where the cordons should be placed.

Since the current response procedures are not constructed around the needs of incident victims (findings of the analysis conducted in *Step 1: Understanding the Application Domain* reported in Chapter 4), it was decided to concentrate the consequent methodological steps towards development of InSiM (*In*cident *Si*mulation *M*odel), which simulates reaction of general public to a CBRN urban explosion. This model could be used by incident commanders for identification of likely dispersion patterns of people around the affected area in a specified time after the explosion. This would support the decision making process related to location of the cordons with information regarding behaviour of the victims. Due to the car-free centres policy introduced to many large British cities (Topp and Pharoah, 1994) and for the sake of simplicity InSiM only simulates behaviour of pedestrians.

It was identified in the literature review (Section 2.2.2.1) that movement is a crucial part of human reaction to an emergency. According to Jiang and Gimblett (2002) movement of a person is influenced by both social interactions with others and the sense of place and space that the individual possesses about a particular location. Social interactions have been frequently discussed by scientists in sociology, psychology and human factor domains. However, as the literature review revealed, sense of space and place has not been broadly considered in geo-simulation models. Therefore, the methodology presented here attempts to bridge this gap and focuses on incorporation of spatial aspects of human behaviour into the agent-based models.

The following sections discuss specific methods and techniques that extend the proposed methodology for development of InSiM. The adopted approaches are briefly described and their selection for this particular case study is justified.

3.3.1 Step 1: Understanding the Application Domain

This step concentrates on understanding how CBRN cordon zones are managed and what guidelines, processes and information sources are consulted during the process. The literature review revealed that this step is omitted by many researchers. However, if a geo-simulation model is developed to support the everyday work of first responders, it needs to, at least partly, fulfill their needs and requirements.

Publications that did include such analysis mostly described the system from observations in essay-like form (e.g. Batty et al., 2003; Castle, 2007). The main limitation of this approach is its unstructured nature, making it difficult to obtain a succinct and transparent view of the situation since the text can only capture the information in a linear way. In addition, the researchers usually collected the information from one source (e.g. Carnival Review Group in case of Batty et al., 2003) resulting in a single-minded view of the situation.

From the review it appears that only Zarboutis and Marmaras (2007) adopted a formal explanation of their system. Their selected task analysis approach is capable of obtaining a detailed description of the response activities (Shepherd, 2000). However, it cannot capture the whole scale of an emergency situation including, for instance, identification of data sources that are consulted during the response operation, critical assessment of the procedures, or recognition of problems and issues that are connected with the currently adopted standard operating procedures.

The use case selected in this research challenges this development step. Since the system is fully functional only during emergency situations, and due to the restricted access to some of the information sources (classified information), observation of a system in operational state is often not possible. In order to gain broad insight into CBRN cordon management, the information regarding the functionality of the system is collected using three different sources:

- to obtain basic knowledge of the system and to understand its related terminology The Civil Contingencies Act (Great Britain, 2005) and its accompanying documents are studied (HM Government, 2005a,b) together with documents related to decontamination of people affected by CBRN substances (Home Office, 2004) and standard operating procedures for HAZMAT (hazardous material) emergencies (IAEA, 2006);
- a more detailed view is gained through discussions with two experienced incident commanders from Nottinghamshire Fire and Rescue Service;
- the results of the analysis are reviewed by a representative from Nottinghamshire Constabulary to obtain an independent opinion on the outcomes.

Soft systems methodology (SSM; Checkland and Scholes, 1990; Wilson, 2001) appeared to be the most appropriate technique for analysis of collected information. In contrast to task analysis methods, SSM approach focuses on identification and in-depth analysis and modelling of the processes involved in the system (Checkland and Scholes, 1990; Wilson, 2001). This technique was successfully applied as a scientifically valid approach to formally analyse complex systems with strong human involvement e.g. to support river rehabilitation and management (Bunch, 2003); to model simulated outpatient services (Lehaney and Paul, 1994); to improve the teaching and learning process (Patel, 1995); and for researching purchaser-provider interactions in the National Health Service (Checkland, 1997). From a disaster prevention and management perspective it offers both pre- and post- disaster applications, e.g. pre-disaster planning of counselling services (Gregory and Midgley, 2000); and post-disaster analysis of communications (Lea et al., 1998).

Due to the highly structured and systematic step by step framework which is capable of analysing the complex and dynamic system from the view of several different stakeholders, it is expected that SSM would provide an objective view of the system under consideration. In addition, the diagrammatical form of its outputs should be easier to comprehend than purely textual explanation, providing a transparent and well integrated description of the system. Moreover, it could also facilitate identification of problems and issues that are embedded deep in the system (Runciman et al., 2007). Hence, after conducting this step, it should be possible to detect the areas with the biggest need for research. The SSM analysis for development of the InSiM are presented in Chapter 4.

3.3.2 Step 2: Experimental Data Collection

To fully understand the nature of CBRN incidents, it is necessary to identify the reactions of people who are present in the area near the explosion. The aim of this development step is to collect such data. In the reviewed publications information regarding behaviour of people involved in the incident has been collected through use of the following techniques:

- real-life observations of the system (e.g. Braun et al., 2005; Castle, 2007; Still, 2000; Zarboutis and Marmaras, 2007);
- analysis of video footage or photographs of similar situations (e.g. Batty et al., 2003; Raupp-Musse and Thalmann, 2001; Murakami et al., 2002);
- analysis of related literature (e.g. Castle, 2007; Murakami et al., 2002; Rahmandad and Sterman, 2008; Wagner et al., 2003);
- surveys in the form of questionnaires or interviewers (e.g. Batty et al., 2003; Castle, 2007).

In general all of these techniques, if applied properly, have been recognised by the broad scientific community as valid approaches to empirical research data collection (Cohen et al., 2007). Therefore, the selection of the most appropriate approach for this research is predominantly determined by the selected use case.

It has not been possible to conduct observations of human reaction to CBRN incidents. Although some video footage or photographs of past CBRN incidents exist (atomic bombings of Hiroshima and Nagasaki during the World War II; Sarin attack on the Tokyo underground railway system in 1995; Anthrax attacks in the United States after 9/11) such material is site specific and often lacks sufficient level of detail for extracting information upon which a model can be populated.

In order to obtain general knowledge about human behaviour in similar type of situations (rapid evacuation on a street level due to a bomb explosion) scientific literature from sociology, psychology and human factor domains is reviewed. The latest research results presented by Drury (2004) and later followed by Drury and Cocking (2007) indicate occurrence of the same kinds of human behaviour patterns and psychological processes across different scenarios, different kinds of disasters with different populations of survivors. The research presented in this thesis inclines towards the belief that people are most likely unable to distinguish between an "ordinary" explosion and a CBRN incident in the first minutes after the blast. It was therefore assumed that the reaction of citizens in the first hour after the explosion will be in both cases the same. This enables the use of findings from research related to any type of sudden, impulsive and location restricted emergency.

However, in order to obtain information at the desired level of detail, additional experiments need to be conducted. For these purposes both quantitative and qualitative research methods can be considered as appropriate approaches to data collection. Due to the lack of research related to understanding effects of the incident location on the resulting human behaviour a definition of a clear set of variables which could be measured by quantitative research methods is not appropriate. Therefore, as a logical first step, it is necessary to conduct qualitative research to gain initial understanding of the situation before it can be quantified. For the purposes of this thesis two qualitative research methods are selected:

- **Semi-structured interviews (SSI):** Unlike structured interviews or questionnaires, where all questions are formed prior to the experiment, SSI are conducted with a fairly open framework (Bryman, 2004). Such flexible nature enables the combination of a structured agenda with the possibility to expand on issues and ideas arising from the interview by asking subsequent questions (Flick, 2002; Oppenheim, 1992). In this research the SSI are used to obtain a bigger picture of the situation, providing enough space for the participant to express in detail how witnessing a CBRN urban explosion would affect their behaviour.

- **Photo elicitation interviews (PEI):** PEI, in contrast, have a clear structure which remains the same for all the participants of the experiment. This approach is grounded on a card sorting technique which is popular for knowledge elicitation (Wagner et al., 2002). During a PEI photographs are used to invoke comments and discussions with the participant (Banks, 2007; Hansen-Ketchum and Myrick, 2008). This research method was used, for example, by Hansen-Ketchum and Myrick (2008) and Radley and Taylor (2003) for data collection in nursing research. Loeffler (2004) conducted PEI experiments to identify the demands of clients on outdoor adventure activities. The capability of capturing knowledge that is triggered by a visual input, evoking greater cognitive response than words alone, is the biggest advantage of this approach (Harrison, 2002; Harper, 2002). The intention of the PEI experiments in this research is to discuss the influence of the particular location depicted on the photograph (*sense of space and place*) has on the behaviour of evacuating pedestrians.

Both of the experimental studies are further discussed in Chapter 5.

3.3.3 Step 3: Experimental Data Analysis

The aim of this step is to analyse the collected empirical data in order to obtain information which can then be further processed and incorporated into InSiM.

Analysis of qualitative data is a complex process. Many reviewed methods and procedures are ill-structured and lack coherence. In this thesis the selection of the most appropriate technique is guided by a review provided in Fielding and Raymond (1998). The evaluated analytical approaches are:

- **Analytic Induction:** This approach generalises the collected data through detection of general statements about the system. In addition, the conditions that are associated with each statement are depicted. For instance Lindesmith (1968) used analytic induction to study under which conditions an individual becomes addicted to drugs.
- **Code-Based Methods:** These techniques have been mostly used for analysis of SSI. They classify the content of the responses into categories derived inductively, i.e. obtained gradually from the analysis of the data. This enables organisation of the material into standardised categories by which the studied system is characterised.
- **Grounded Theory**: The aim of grounded theory is to provide a rationale for a theory that is empirically derived. Hence, rather than initially selecting theoretical framework that is applied to study the system, grounded theory focuses on extracting concepts that form a basis from which a new theory can be generated.
- **Discourse Analysis:** This category does not represent a coherent paradigm but rather groups together several approaches with different epistemological roots. In general, all these diverse methods concentrate on investigation of language in use and language in social context. Therefore, these methods analyse the system from the perspective of how it is interpreted by the research participants.

- **Content Analysis:** This approach seeks for identification of patterns in the collected data. Similarly to code-based methods, it also organises the data into implicit categories. In addition, it also enumerates how many times the context of the particular category has been mentioned in the collected material. Hence, it is possible to partly quantify (by identifying frequencies) the qualitatively obtained data.

For the purposes of this development step the content analysis approach was selected to process the empirical data from both experiments. Although the analytic induction and code-based methods were further evaluated as potentially relevant, their biggest limitation is that they do not provide any quantifiable results. This would challenge the consequent model development steps where the information has to be quantified to populate different behavioural categories of agents in InSiM. Since this research does not aim to propose any new theories, a grounded theory approach is considered as not suitable. Similarly, discourse analysis cannot provide outputs in a form that can be easily transformed into concepts that can define an agent.

The analysis is reported in Chapter 6.

3.3.4 Step 4: Model Evolution and Development

This methodological step aims to develop a conceptual model of InSiM which depict its architecture and functionality. For this purpose information obtained in the previous development steps is used. According to the analysis of the scientific literature a conceptual model is formed from the following building blocks:

- **the simulation environment**: depicting the format and characteristics of the synthetic space within which the agents interact;
- **agent specification**: providing definition of the parameters agents are

characterised by and specification of algorithms which describe their behaviour;

- **general model characteristics**: combining model components and parameters which are related to overall functionality of the model.

It is not possible to review and evaluate all of the possible research methods that could be applied for definition of the above building blocks. This is mainly due to the enormous diversity of the models available (as discussed in the literature review). Therefore, the following approach only considers methods that suit the needs of InSiM.

The simulation environment

If InSiM should be used for identifying locations of people during a real CBRN incident, the simulation space needs to represent a real geographic area. According to the Home Office (2004) one of such areas is a centre of a city which often has high concentration of people. Such location was for instance also selected in models developed by Batty et al. (2003) and Shendarkar et al. (2006). These models also define the simulation environment by using real geographic data to provide application of the model for solving real-life problems. To enable incorporation of realistic environments the InSiM simulation space is defined based on data extracted from high resolution OS MasterMap database (Ordnance Survey, 2009). Use of such databases also extends its application for different geographical areas over and above those defined in the case studies.

The second consideration that needs to be evaluated is representation of the *sense of place and space* into agent's behaviour. This is done by defining the agent-environment interaction with respect to the behaviour of its counterpart in the real-life system. In the reviewed models this was represented by defining agent's movement towards specific destinations by following the *path of least effort*. This route is, for instance, defined as the closest geometrical distance to the nearest emergency exit (e.g. Castle, 2007) or exit from the affected area

(Shendarkar et al., 2006), by the amount of smoke and fire in the tunnel (e.g. Zarboutis and Marmaras, 2007), and amount of people in the neighbourhood (Henein and White, 2007). In InSiM the same approach is adapted. The findings of the experimental data analysis are used for definition of the environmental characteristics that determine the path of least effort.

Agent specification

The selection of parameters that characterise an agent and algorithms that defines its behaviour was according to the reviewed models determined in the following ways:

- based on assumptions of the researchers about the behaviour (e.g. Mysore et al., 2006; Musse et al., 2007);
- extracting the information from reviews of scientific literature (e.g. Carley et al., 2006); and
- by collecting data through empirical research (e.g. Castle, 2007).

The data collected in *Step 2: Experimental Data Collection* are used to determine agent's specification in InSiM. Descriptive statistics (frequency distribution, mean, and standard deviation) that characterise distribution of the population sample in the experimental studies are used to specify the values of the parameters and the different behaviour patterns of agents. According to Castle (2007) and Bryson (2004) the complexity of the algorithms, requirements put on the number of agents, and the level of detail that need to be depicted in the environment are the most significant factors that guide decision on what reasoning process should be used to represent agent's decision making. Hence, the decision on what mechanism to select is guided by these recommendations.

General model characteristics

These characteristics are related to specification of the input and output data in InSiM. The input data consist of the geographical datasets that are used for specification of the environment. InSiM aims to provide information on the distribution of people in a city centre in different time intervals after the explosion. Hence, the output contains OSGB National Grid coordinates that specify locations of the agent on in the environment once a simulation run is completed. The format of the output data is dependent on the methods and tools that are be used for its consequent processing.

Number of agents used in a simulation run, their distribution on the simulation space, and duration of the simulation is determined based on the definition of the use case by which InSiM is tested.

A detailed description of this methodological step and the conceptual model of InSiM are presented in Chapter 7.

3.3.5 Step 5: Model Implementation & Definition of Case Studies

This step is the most technical part of the agent-based development process. Although significant attention is put on actual coding of the designed model, several considerations need to be assessed before the programming takes place. Axelrod (2007) argued that selection of the most appropriate programming language is imperative because it often determines further use and extendibility of the model. As the literature review indicated, a number of platforms that could support the model development exist e.g. Repast (Repast, 2009), Swarm (Swarm, 2009), NetLogo (NetLogo, 2009) or Jack (Winikoff, 2005; Howden et al., 2001). Therefore, it is desirable to test whether utilisation of any of these platforms would facilitate the development process as for instance did Castle and Crooks (2006). Castle and Crooks further specify that use of these platforms can increase the reliability and efficiency of the model since they have mostly been created by professional developers.

For the purposes of InSiM Repast, NetLogo, and CGSagent (an in-house agent-based modelling environment developed by Dr Jerry Swan) were selected as potentially usable platforms. They have been evaluated by guidelines provided in Castle and Crooks (2006). In the time of the evaluation Repast and NetLogo were not suitable since their capabilities of running the simulation on geographic network (format of InSiM simulation space) were limited. Therefore, it was decided to use CGSagent. Although this platform is not as extended as the other two, it's largest advantage is that its functionality can be consulted directly with the system developer.

Rapid prototyping is adopted as the most suitable software development process (Sommerville, 2007). This approach involves iterative development which is very flexible to incorporation of changes if required. In this research each iteration introduces more complex algorithms into the fully operational model.

In similar fashion to Castle (2007) and Batty et al. (2003), the definition of the case studies by which InSiM is tested is conducted with the domain experts. In this instance incident commanders from Nottinghamshire Fire and Rescue Service were asked to identify the length of the simulation run and the size of the explosion.

Implementation of InSiM and definition of the case studies is further discussed in Chapter 8.

3.3.6 Step 6: Analysis of Results

The data generated by the simulation need to be further analysed to obtain answers to the questions for which the model was developed in the first place.

However, the literature review revealed that not enough attention is put on the results assessment. Axelrod (2007) and Zarboutis and Marmaras (2007) discussed general approaches that can be applied to generate the desired information. Axelrod demonstrated a clear preference to a qualitative (descriptive) approach, while Zarboutis and Marmaras concentrated on application of quantitative techniques.

Many models evaluated in the literature review were developed for the purposes of testing novel algorithms to increase the simulation performance. They therefore focus on depicting the change of the simulation speed (represented by simulation time) needed for accomplishing a specific set of activities (e.g. Habibi et al., 2002; Hu, 2006; Raupp-Musse and Thalmann, 2001; Raymond and Reed, 2006). This approach is, however, not sufficient for detection of any patterns emerging from the interaction of agents. This indicates that selection of the most appropriate analytical method is dependent on the purpose for which the model is developed.

Qualitative and quantitative approaches can produce different outcomes which can be equally valuable. It was therefore decided that the analysis of the InSiM generated data should be conducted from both of these perspectives. The purpose of InSiM with respect to this research is to provide evidence for addressing the research questions. Therefore, the analysis should focus on identifying how incorporation of real-life information into the modelling process affects the dispersion patterns of the agents around the city centre.

For the analysis three different approaches were selected to gain different views on the generated data. These are:

- **Raster-based analysis**: The distribution of the agents is converted into a continuous surface depicting their densities within the city centre. This type of analysis was for instance used by Batty et al. (2003). In this approach the difference between two distributions generated by different setups (i.e, incorporating different level of real-life information into agent's behaviour) of InSiM can be detected by comparing the density rasters. Two methods for evaluation of the differences were selected: visual analysis (Lu et al., 2004) and image differencing (Sohl, 1999). While the former one is based on subjective assessment of the difference, the outcome of the later one is an automatically generated raster of changes. The results of the analysis are evaluated through visual analysis by providing textual description of the emerging patterns as was for instance done by Helbing et al. (2000) and (Zarboutis and Marmaras, 2007). Due to the clustered nature of the data, it was not feasible to apply any formal statistical tests (see Chapter 9 for further information).

- **Spatial statistics**: In this instance spatial statistics refer to techniques that can look for evidence of independence at local level, i.e. between a pair of agents coming from different simulation configurations. The relationship can be detected by application of a G-function which assesses the nearest neighbourhood distance from each agent from the first distribution to the nearest agent from the second distribution (Diggle, 2003). The aim of this analysis is to identify whether the agents from the two distributions are clustered. Cluster analysis was, for instance, used by Eubank et al. (2004) and Rahmandad and Sterman (2008). However, these were applied to one-dimensional data only (propagation of a disease on a social network).

- **Conventional statistics**: In this analysis the 2D information (location of agents on the simulation space) is generalised to a single dimension representing distance. This approach was, for instance, used by Batty et al. (2003) who compared average distance travelled by agents in two different simulations. With respect to InSiM the differences between the distances are compared with application of goodness of fit test which assesses whether any two distributions of the agents are from the same population. In order to identify whether to use parametric Student's t-test or non-parametric Wilcoxon signed-rank test the distributions need to be assessed for normality. This can be done by plotting the observed distribution of the agents in form of histogram against corresponding normal scores of the same mean and standard deviation.

The specific null hypotheses which are tested by the three methods, as well as the results of the analysis and shortcomings of the adopted approaches, are further discussed in Chapter 9.

3.3.7 Step 7: Model Evaluation

The literature review revealed that an assessment of the developed model is crucial in order to identify its usability for disaster management purposes. As has been discussed the most commonly applied evaluation approach consists of three steps: validation, verification, and calibration (Batty et al., 2003; Castle, 2007; Still, 2000). This approach was therefore also used for evaluation of InSiM.

- **Validation** evaluates to what degree the model matches the real-life situation it represents (Crooks et al., 2008). Since InSiM is not developed with use of data that depicts a real CBRN incident, validation *per se* (as for instance conducted by Batty et al., 2003) is not possible. However, the behaviour of agents is instead assessed against reactions that were reported in the empirical research.

- **Verification** makes sure that the implemented model corresponds with the developed conceptual model (Crooks et al., 2008). The adopted software development process (rapid prototyping) requires verification of the newly implemented algorithms after every iteration. Therefore the model's operational accuracy was regularly tested. The verification tests were performed on small datasets containing one to several agents in order to easily observe the effects of the newly added component on the final behaviour.

- **Calibration** corresponds to fine-tuning of the model to a particular context (Crooks et al., 2008). Similarly to validation of InSiM, it is not possible to identify what is the best fit of the key model parameters to realistically depict the response to a specific CBRN explosion. Therefore, the calibration is performed through sensitivity analysis of the key model parameters (as suggested for instance by Sargent, 1999) to identify to what degree their settings influence the final dispersion patterns of the agents. It is not possible within the scope of this thesis to test dependencies of the whole range of model parameters. To keep the analysis transparent, only one parameter was tested at a time. This approach was also adopted by Castle (2007) who tested nine key model parameters (e.g. route-choice defined by passenger type, walking speed weighted by age, gender, etc.) and Eubank et al. (2004) who evaluated three main factors (mitigation effort, delay in implementing mitigation efforts, and whether people moved about while infectious). They argued that this small number of tests should be enough to understand how the model in general reacts to the changes.

More detailed information regarding the evaluation process can be found in Chapter 9.

Chapter 4

Understanding the Application Domain

4.1 Introduction

The first step of an agent-based model development process is a clear definition of the problem the geo-simulation model should address. The accuracy of its description depends largely on the knowledge the developer possesses about the application domain. Therefore, sufficient information about the system under investigation is necessary before a conceptual model of the geo-simulation application can be constructed (Sargent, 1999).

The aim of this chapter is to provide a background and motivation for the development of InSiM. The response to a CBRN incident consists of a large number of very complex processes. This thesis focuses on disaster management process connected with the placement of inner and outer cordon zones around the area affected by the CBRN incident which is throughout this chapter abbreviated to INCROMS (*IN*cident *COR*don *M*anagement *S*ystem).

INCROMS involves a large number of people who possess diverse opinions on what needs to be considered when deciding the optimal locations for the cordons. This large diversity of views cannot be clearly described with the use of natural language. It requires a structured form for clarity and brevity. There-

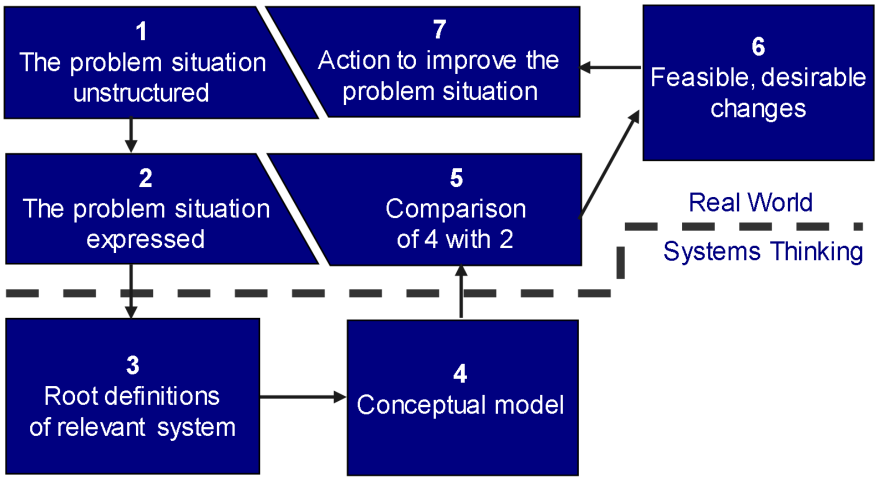

Figure 4.1: Diagram representing seven stages of SSM, adopted from Checkland and Scholes (1990).

fore, a process modelling technique soft systems methodology (SSM) (Checkland and Scholes, 1990; Wilson, 2001) is used to formally document INCROMS. This technique places special emphasis on people's perception, together with their experience and knowledge of the system. SSM focuses on:

- representation of divergent views about the definition of the problem;
- encapsulation of soft problems that originate in fuzzy and poorly defined situations;
- resolving what is termed a "problem situation" which is characterised by complex and in most cases several connected unstructured problems (Checkland and Scholes, 1990; Wilson, 2001).

In addition, this technique supports identification of issues and proposes alternative solutions which can improve the system's functionality.

SSM is divided into seven distinct stages and each stage is assigned to one of two categories based on different perceptions of the problem situation under consideration taken by the analyst:

- the real world view which aims to describe the current system, and

Stage	Name	Description
1	Problem Situation	Basic research into the problem area
2	Rich Picture	Expressing the problem situation by drawing a diagram
3	Root Definition	Selecting the view on the situation, "*Whats*"
4	Conceptual Model	What the system must do, "*Hows*"
5	Comparison of Conceptual Model with Real World Situation	Comparing stage 4 with stage 2, identification of their similarities and differences
6	Changes Identification	Identifying feasible and desirable ways of improvement
7	Recommendations for Improvement	Suggestions for implementation of the changes identified in stage 6

Table 4.1: Stages of SSM; table created based on information extracted from Checkland and Scholes (1990)

- the systems thinking view presenting the ideal solution for the problem situation (Checkland and Scholes, 1990).

A diagram depicting these stages can be found in Figure 4.1 and their succinct description in Table 4.1. Each stage expresses an iterative process that requires each iteration to be discussed directly with representatives involved in the system (Checkland and Scholes, 1990). The following sections demonstrate application of all seven stages of SSM to INCORMS. Each section contains a description of activities that characterise the specific SSM step followed by presentation of results obtained from the analysis. In addition, Section 4.9 discusses a particular issue SSM revealed as problematic which this thesis attempts to address in the subsequent chapters by development of InSiM.

4.2 Stage 1: Identification of the Problem Situation

The aim of this initial stage is to recognise and explore the problem situation under consideration. In this study the system is looked at from two levels. At the first level (Level 1), relevant literature discussing existing national guidelines comprising general recommendation for management of incident cordon zones is reviewed to gain insight into the system.

To understand the difficulties and challenges that are involved in the related decision making process a close collaboration was established with Nottinghamshire Fire and Rescue Service and Nottinghamshire Constabulary. Three experienced incident commanders were interviewed to ascertain their views and understandings of the responsibilities and priorities of their respective service. The text in the Level 2 section explores local implementation of the cordon placement procedures from the perspective of the interviewed incident commanders who were encouraged to discuss their experience with application of the provided guidelines into actual emergency response.

4.2.1 Level 1: Incident Site Management National Guidelines

A generic national framework for managing the local multi-agency response to, and recovery from, emergencies has been established in the UK (HM Government, 2005b). It specifies that the emergency services should establish control over the incident as soon as possible. The incident commanders, who manage the emergency response and co-ordinate activities of the blue-light services, have to assess the affected area and subsequently setup distinct inner and outer cordon zones (Figure 4.2).

The purpose of the inner cordon is to secure the contaminated area and protect the public. It also serves to preserve any evidence of the crime for police investigation. Emergency services personnel are allowed to access that zone through designated cordon access points and must be appropriately dressed and equipped. Everybody leaving the inner cordon must be decontaminated. Specially designed units for the decontamination of response personnel need to be setup first. Additionally, mass decontamination units to which the exposed public are directed and an ambulance decontamination unit for victims suffering serious injuries are constructed nearby.

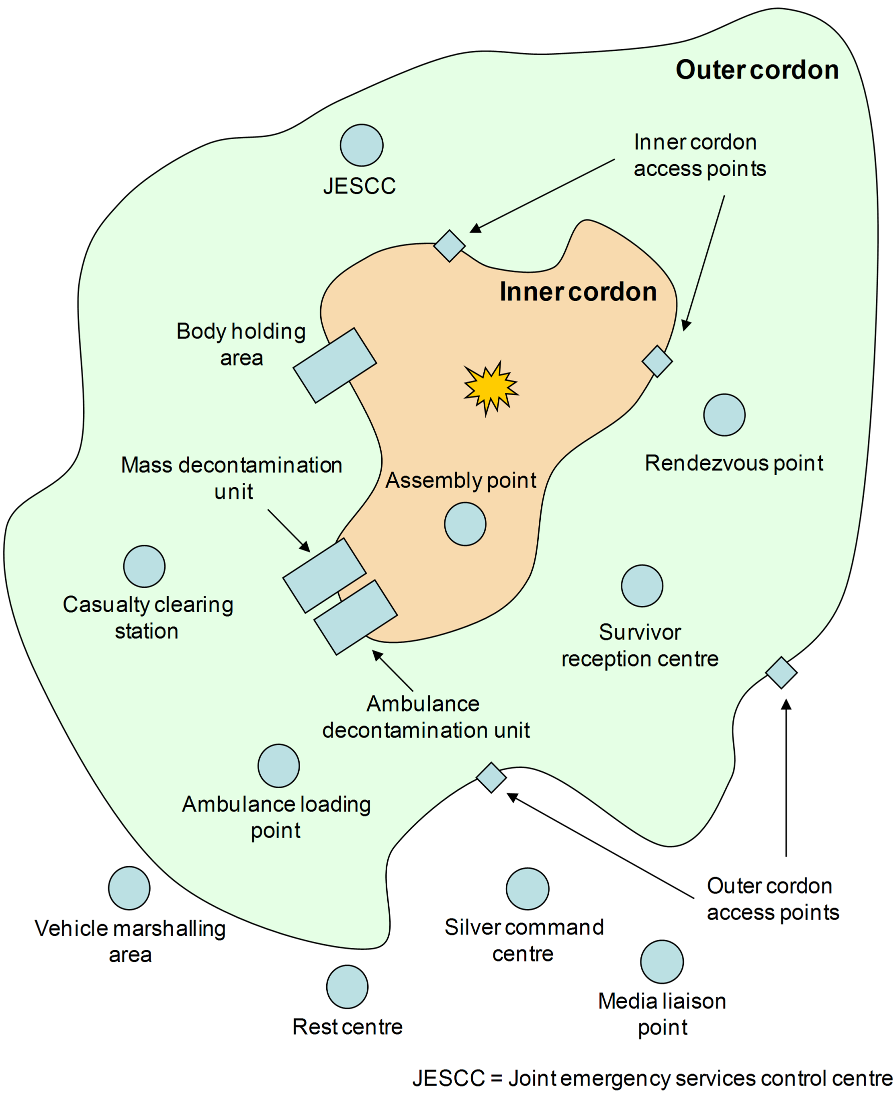

Figure 4.2: Incident site management national guidance adopted from HM Government (2005b).

To support the operational activities an outer cordon zone is next established around the inner cordon. This may cover an extensive area for which all access and exit points must be controlled. The main purpose of the outer cordon is to provide sufficient space for the placement of key off-site functions and facilities. The outer cordon also acts as an additional safety zone should the contaminated material unexpectedly spread. For more information about both cordon zones the interested reader should consult HM Government (2005b).

4.2.2 Level 2: Operational Procedures for Cordons Placement

Inherent complexities, uncertainties and the dynamic nature of a CBRN incident present major challenges to the operational management of the response. Incident commanders often rely on personal experience, intuition and local knowledge about the incident site and its surroundings. Such inputs result in subjective judgements and the final outcome in practice varies from person to person. Therefore further negotiations are necessary, which often produce a general slowdown in the decision making process.

The Civil Contingencies Act (Great Britain, 2005), related guidelines (HM Government, 2005b), and local standard operating procedures provide specific requirements on what needs to be included and what issues need to be addressed in a local INCORMS. The guidelines do not, however, recommend a decision making process nor specify a method for determining the positions or extent of either inner and outer cordons, nor the best locations for the placement of key off-site facilities. To compensate for this lack of information HAZMAT (Hazardous Material) operational procedures are instead applied to associated problems in a local INCORMS (IAEA, 2006).

The inner zone initially comprises a circle around the incident with 400 m radius. If fully implemented, this would cover an area of approximately 50 ha. However, the size can be reduced in some places by shortening the radius to

150 m once carefully inspected following a set of general risk assessment procedures. The outer cordon is setup appropriately to the size and amount of required resources and the layout of the surrounding area. Both cordons are controlled by the Police. Beyond this area no special procedures, controls or restrictions are required.

4.3 Stage 2: The Problem Situation Expressed

In this step the problem situation identified in the initial stage is expressed in the form of a diagram called a rich picture. The aim of the diagram is to capture and organise all main components of the system and their relationships in a graphical cartoon-like representation (Monk and Howard, 1998). In this research two rich pictures were constructed; one for the inner cordon and one for the outer cordon (Figures 4.3 & 4.4). The collected information indicates that the constriction of inner and outer cordons in INCORMS represents a sequential decision making process in which the placement of the outer cordon is to a large extent dependent on the location of the inner. The high complexity of this situation requires such operations to be considered as two separate sub-systems (Figure 4.5). The overall situation could be described in one picture but it would handicap the depiction of information at the desired level of detail.

Each picture includes primary stakeholders in the decision making process which are the main Category 1 responders as defined under the Civil Contingencies Act (Great Britain, 2005), i.e. the organisations at the core of emergency response (e.g. fire and rescue services, local authorities, and NHS bodies). The topmost part of each picture illustrates the various datasets and sources of information related to decision support requirements. Information about the actual incident is updated on a regular basis with blue-light services reports supplied from the incident site. This information is then conflated and considered by the incident management team alongside other material such as records on the behaviour of dangerous substances, meteorological forecasts, topographic maps and digital elevation datasets. To capture different views on the process each stakeholder's relevant concerns and desires are represented using "thought bubbles". The interrelationships and information flows are expressed using directed arrows with action labels. Pictorial symbols are placed next to the main components for the purpose of emphasis.

The management activities for setting-up inner and outer cordons are more or less the same. However, the decision making processes differ. The placement of the outer cordon has to be evaluated from a broader perspective since the designated zone needs to include sufficient space for the required facilities. It must also offer reasonable connections to: transportation networks, hospitals, survivor shelters, etc. It is also the space in which resources and personnel from all services are assembled.

4.4 Stage 3: Naming Relevant Systems and Constructing Root Definitions

SSM uses concepts of hierarchy, control, and emergent properties to identify "relevant systems" which could provide useful insight. Identification and naming of such systems is based on logical analysis and constriction of one or more "root definitions". Each root definition provides an encapsulation of the problem situation, as seen from a particular perspective, and is the core component of collective activities that are depicted in the rich picture(s). The main element in the root definition is a transformation process that takes some entity as input, and changes that entity, to produce a different or modified form of that entity as an output. The structure of the actual root definition is written as a sentence of strictly defined schema. For more information and detailed guidance on how to properly construct a root definition consult Checkland and Scholes (1990). In order to check the correct formulation of the sentence six elements are used to

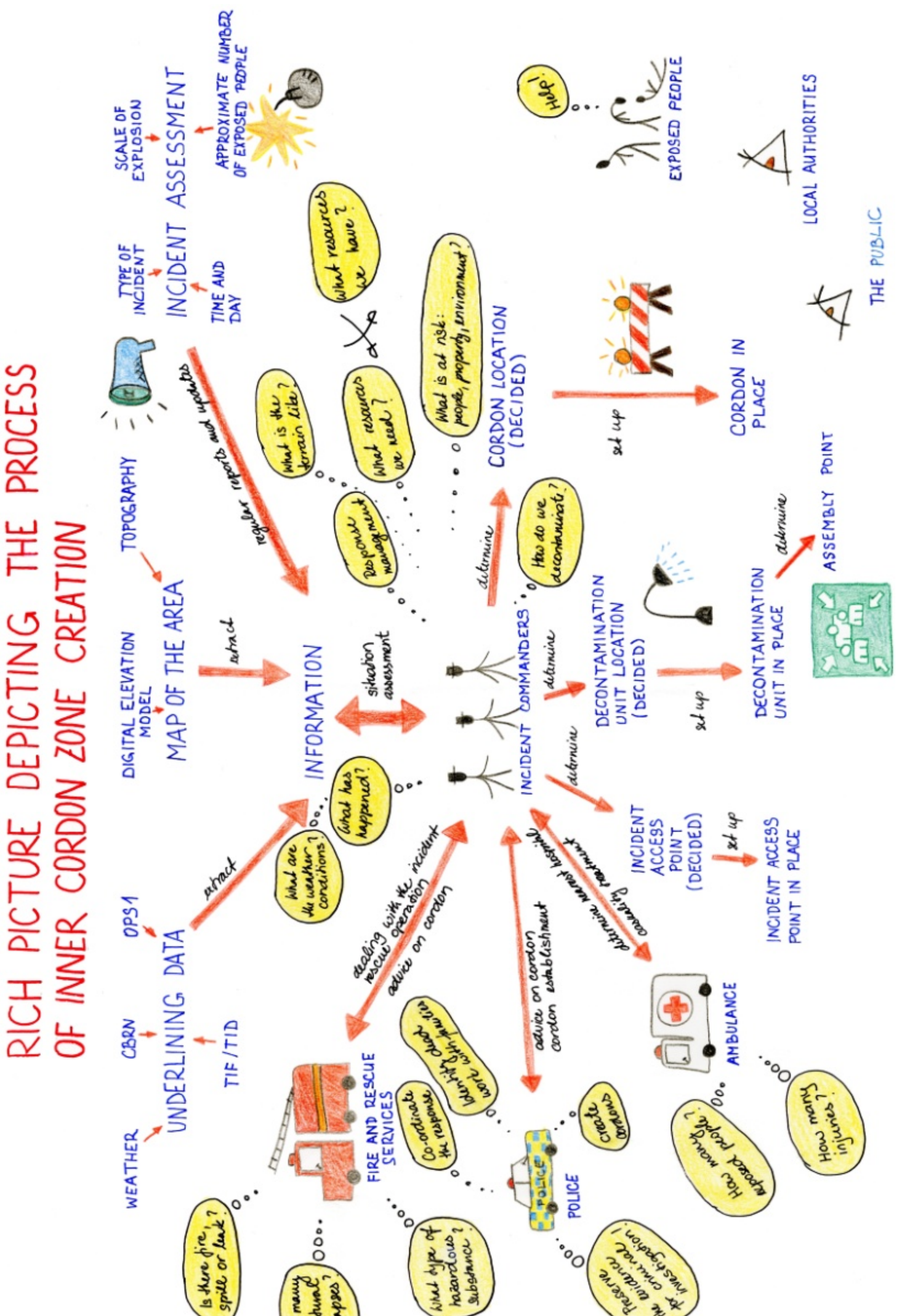

Figure 4.3: Rich picture depicting existing local procedures of inner cordon placement.

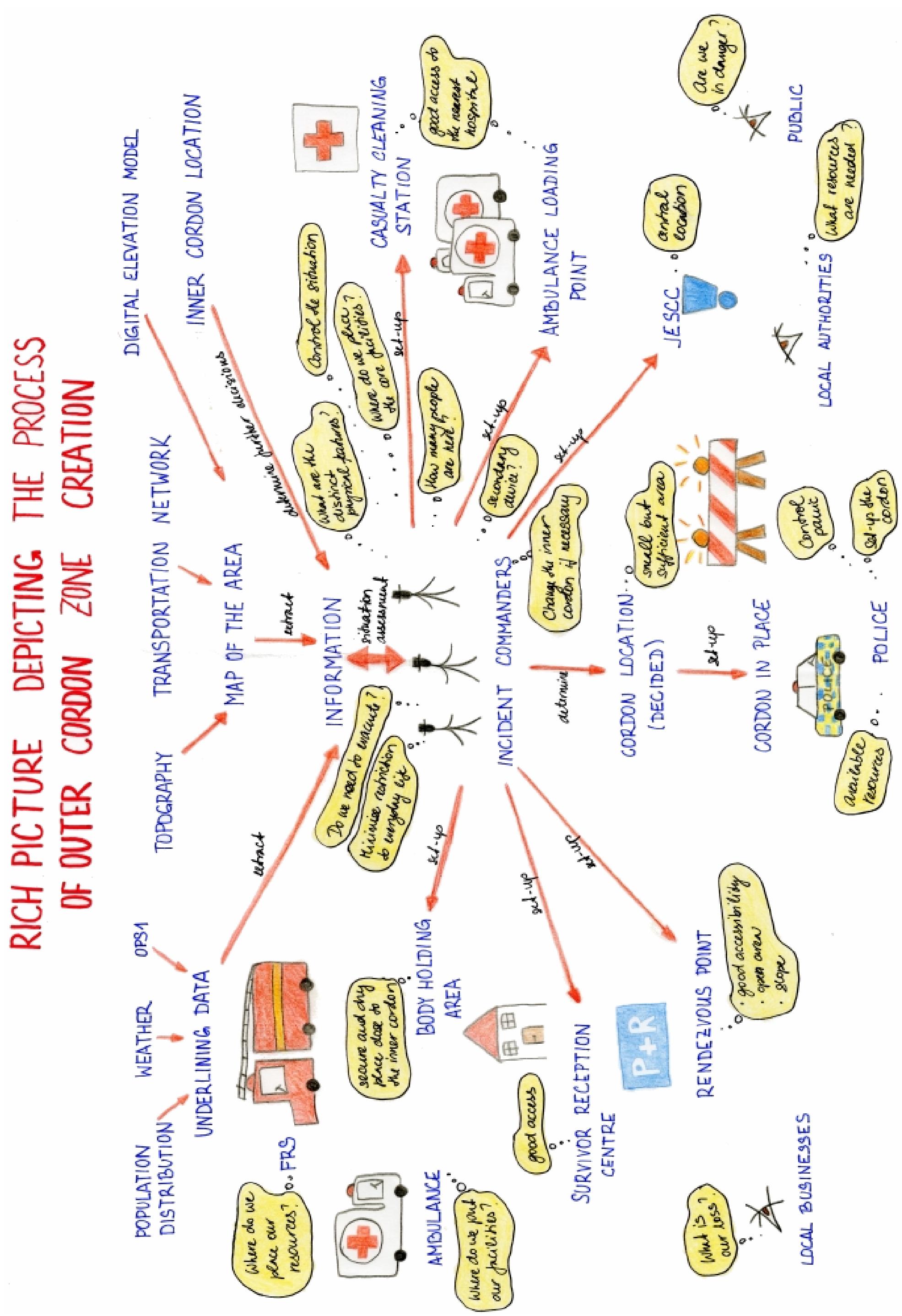

Figure 4.4: Rich picture depicting existing local procedures of outer cordon placement.

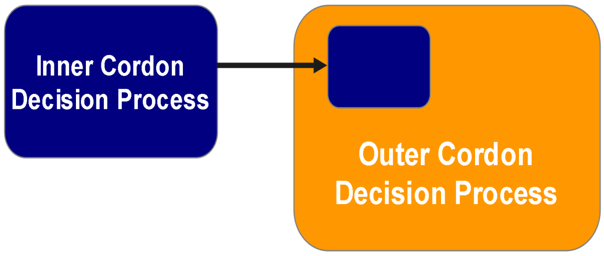

Figure 4.5: Sequential diagram of two sub-systems considered.

test the words inside it (Wilson, 2001):

C (*C*ustomers): everyone who obtains benefits or drawbacks from the output of the transformation process;

A (*A*ctors): those who would perform the activities defined in the resultant conceptual model if they were to map onto reality;

T (*T*ransformation processes): the conversion of input to output;

W (*W*orld view): makes the transformation process meaningful in context;

O (*O*wner(s)): those who have proprietary rights over the system defined with a concern for the performance of the system;

E (*E*nvironmental constraints): elements outside the system which are taken as given and cannot be changed.

The input entity of the transformation process selected in this study is "requirement for cordons" and a single root definition has been created based on the perception of incident commanders and their requirement to meet the essential need for protection and provision of recognised barriers. Although two rich pictures were created to provide more detailed insight into INCORMS, one root definition is sufficient for further analysis. This root definition captures characteristics of the whole INCORMS and reads:

An incident commander owned system, operated by incident response officers, to place incident cordon zones, in order to protect the public, treat

Element	Description
C	first responders, general public, victims, local government, business owners
A	incident commanders, emergency response personnel, command and control personnel, administrative and technical staff
T	cordons required ⇒ cordons placed
W	protection of public and response personnel, treat victims, secure the incident site for police investigation, facilitate the work of the emergency services, enable faster and well coordinated response, provide safer and sufficient working environment, limit or minimise disruption to local businesses
O	incident commanders
E	incident extent and type, physical environment, accessability, availability of resources, weather conditions, behaviour of victims and general public

Table 4.2: CATWOE analysis of the root definition.

victims, secure the incident site, provide a working environment for first responders and either limit or minimise disruption to business activities, while considering the incident type, physical environment, infrastructure and available resources.

4.5 Stage 4: Building Conceptual Models

The purpose of developing a conceptual model is to identify each operational activity that would be necessary to carry out the process described in a root definition. It is used to pinpoint and help organise the essential concepts of the system. This enables system stakeholders and system analysts to develop their own model of an "ideal" system for the job required as well as to identify the criteria to be used for choosing the best alternative solution.

SSM does not require the conceptual model to be specified by use of traditional object-oriented approaches such as UML diagrams which are commonly used in software engineering to provide a formal specification of software components during the design phase. In SSM terminology the conceptual model does not provide a description of a system that is to be engineered. The model instead assembles the minimum set of activities that would be needed to perform the transformation process as specified in the root definition (Checkland and Scholes, 1990; Wilson, 2001). The configuration of the model is based upon logical dependencies with relationships depicted through directed-arrow links. The creation of a conceptual model is based on three questions, related to the transformation process, such that the answers could be developed into different subsystems of a more general model:

1. What has to be done to commence the transformation process?
2. What actions are involved in the actual transformation?
3. What must be done to implement the output of the transformation process?

Figure 4.6 depicts the conceptual model of an ideal INCORMS. Each activity represents a specific sub-system. The first question is answered by the three topmost activities: *Manage Resources*, *Gather Knowledge* and *Collate Information*. The output of these activities feeds into the core decision making process that answers the second question. The decision making process is characterised by the following activities: *Protect*, *Decide*, *Establish Working Environment*. The final activity is *Cordon Placement* which is connected with the last of the three listed questions. It has been depicted in orange to emphasise that the output of this sub-system is also general output of the whole INCORMS.

To gain closer understanding of the decision process determining the locations of the cordons, the activity *Decide* was further analysed. The aim of such analysis was to gain additional knowledge about the processes that are hidden in the general labels. This will facilitate identification of problems and issues in the consequent SSM step. As each activity effectively forms a sub-system, additional root definitions (see Appendix A) and conceptual models (see Appendix B) were created. Similarly to the general INCORMS conceptual model, the output activities are depicted in orange. These outputs are consequently fed into the other higher-level activities.

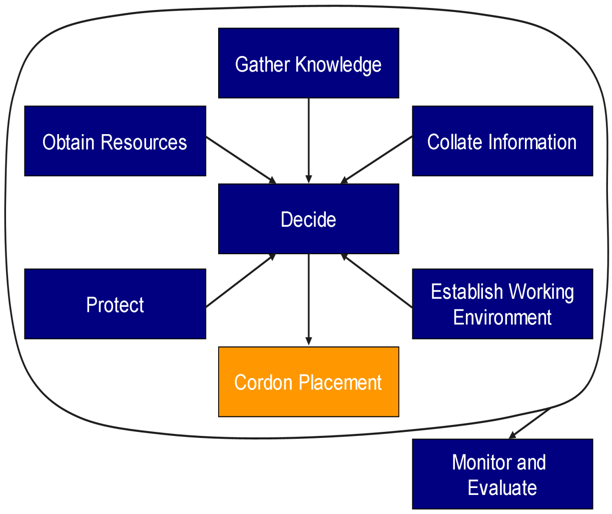

Figure 4.6: Conceptual model of the whole INCORMS.

To ensure coherence of the overall model each of the activities, as well as the functionality of the entire system, is monitored to determine whether it is performing at an acceptable level. Additional control actions are specified to guarantee the achievement of the goals defined in the root definition (Wilson, 2001).

4.6 Stage 5: Comparing the Conceptual Model With the Real World

The conceptual model must be compared with the real world for the purpose of revealing problematic or malfunctioning activities which might then be changed so as to enhance the overall operation of the existing system. Checkland and Scholes (1990) argue that the most common way of comparison in SSM is formal questioning where the questions are formed from the conceptual model, i.e. ideal system, and the answers derived from the rich picture(s) which represent the current situation. In general, each activity identified in the conceptual model is evaluated. First, a description of how that activity is currently realised is recorded. Subsequently, an investigation of potential changes is undertaken in collaboration with the system stakeholders and one or more alternative solutions proposed. The results of the comparison are presented in Table 4.3.

4.7 Stage 6: Identification of Changes and Recommendations for Improvement

The sixth stage of SSM concentrates on the definition of changes to the existing situation which would lead to its improvement (Checkland and Scholes, 1990). The following possible changes to the existing system were identified:

- Provision of more specific guidelines and working procedures for local implementation of INCORMS.
- Establishment of standardised format and regular updates of information regarding location, availability, quality, and quantity of resources that can be called upon once the incident strikes.
- Establishment of understanding and subsequent application of state-of-the art technology related to management of local and remotely stored information would minimise the time needed and problems related to its acquisition and conflation.
- Application of standardised format of information and services would facilitate interoperability between organisations involved in the response operation. This would also support exchange of knowledge and information.
- Establishment of a knowledge base containing information related to previous response operations could facilitate training of junior officers. It could also encourage identification of incorrect assumptions to avoid the same mistakes in the future.
- Cooperation with human factors and psychology researchers specialising in behaviour of people under severe life threatening conditions could

Activity	Exists?	How?	Who?	Judgement	Alternatives?
Obtain resources	Yes	discussions between response organisation, requesting and accessing locally and remotely stored resources, call for reinforcements and Incident Response Units (IRUs)	incident commanders, command and control personnel	sufficient but can be improved	up-to-date list of available resources and their locations; improve discussion effectiveness by introducing commonly agreed structure prepared prior to the incident
Gather Knowledge	Yes	discussions, links to external experts	incident commanders, invited experts	no formal system exists	records of collective knowledge and experience from previous operations; access to such information; regular meetings and team building exercises; division of responsibilities prior to the incident
Collate information	Yes	access to digital and analogue databases, tactical updates every 20 minutes, request and obtain access to external sources of information (CCTV footage, weather forecast, etc.)	incident commanders, administrative and technical staff, command and control personnel	not effective	use of state-of-the-art technology for information acquisition; training of response staff, employment of analytical experts trained specifically in disaster management; regular inspections of links to crucial datasets; regular updates of information; regular simulation exercises
Protect	Yes	providing the public with warnings, advice and information; arrangements for evacuation; setup of cordon zones; triage; rescue trapped people	incident commanders	requires additional attention	understand general behaviour of affected public and consequently adapt the response; improvement of cordon setup procedures, optimisation of cordon placement based on plume prediction and prediction of location of affected people
Decide	Yes	discussion, ad-hoc information analysis; limited use of computerised tools; regular simulation exercises	incident commanders	no formal system exists	use of computerised systems for decision support; training of response staff; employment of analytical experts; team building exercises
Establish working environment	Yes	discussion, evaluation of the incident site and the neighbouring area, negotiations	bronze commanders	dtto	dtto
Cordon placement	Yes	placement of the physical barriers	Police	slow	staff reinforcements from other response organisations or armed forces
Monitor and evaluate	Yes	monitoring the progress based on the standard operating procedures, operational debrief, tactical meetings every 20 min	incident commanders, on site officers in charge	sufficient but can be improved	use of integrated sensor networks with automatic updates; computerised tools for information logs, staff training; regular simulation exercises; identify what needs to be monitored and evaluated and how

Table 4.3: Comparison of the INCROMS conceptual model with the real world in a form suggested by Checkland and Scholes (1990).

help to prepare more realistic procedures for management of contaminated people.

- Investment in state-of-the-art simulation tools which can be used for evaluation and training of different response tactics or for prediction of incident spread or movement of people could help to better prepare for future events.
- Development of specifically tailored computer-aided dispatch and decision support systems could empower effective management, optimisation and timely delivery of first responders' services.
- Creation of locally or regionally accepted procedures for monitoring and evaluation.

4.8 Stage 7: Taking Action to Improve the Problem Situation

The last stage of SSM specifies actions which need to be taken to assess whether the suggested changes are desirable and feasible (Checkland and Scholes, 1990). Hence, before any of the proposed changes can be implemented into the existing INCORMS they need to be carefully evaluated in terms of return of investment. Such assessment can only be done by stakeholders of the system. This process can be very time consuming if it is to be conducted properly. It needs to be discussed with more than three incident commanders to obtain opinion that could be further generalised. This stage is not essential for the purposes of this thesis, and an evaluation was not therefore conducted. However, for the sake of completeness of the SSM analysis, the following considerations, against which the changes can be evaluate, are provided:

- the cost of new hardware and software,
- the extent and cost of training for operational personnel,

- the assets that the change brings to the existing system and their significance,
- the level of quality and accuracy related to use of suggested tools or procedures, and
- the extent and cost of additional resources.

This is only a very short list which is limited to knowledge gained during the INCORMS analysis. It was found sufficient for the purposes of this research. Nevertheless, additional research needs to be done if the outcomes of the analysis should be used for other purposes.

4.9 Conclusion

The SSM analysis conducted in this chapter revealed a number of problems and issues embedded in the locally or regionally implemented INCORMS. Due to the complexity and diversity regarding exact definition of actions that can improve the existing system, it was decided to only concentrate on identification of one, by which the aim of this thesis can be addressed.

The analysis revealed that the current decision making process by which the most appropriate locations of both cordons are determined does not, in any way, consider behaviour of affected people. This is for instance demonstrated in the rich pictures (Figures 4.3 and 4.4) where the only consideration related to the victims is their approximate number. This finding supports the conclusions from analysis of the response to 7th July 2005 London bombings highlighting that the needs of the incident victims are not to a large degree acknowledged during the response operation (London Assembly, 2006).

However, this information is essential if the victims need to be assembled for decontamination. Incident commanders need to know their location in order to allocate appropriate numbers of officers that could lead them to the designated decontamination units. In the currently adopted INCORMS the decontamination units are setup on the perimeter of the inner cordon (see Figure 4.2). However, exposed people are very likely to be dispersed throughout the neighbourhood by the time cordon is setup and the mass decontamination units assembled. Therefore, there is an apparent trade-off in terms of protection priorities between the management of the incident victims, and the prevention of further victims which focuses on protection of blue-light personnel.

The SSM analysis revealed that an agent-based model that can simulate behaviour of affected people could be of an asset to incident commanders. Such a model would have potential application for:

- simulating the reaction of affected public to make incident commanders aware of what to anticipate;
- testing different strategies for placement of the cordon zones and the off-site facilities (specifically mass decontamination units) and analyse their implications;
- identification of limitation of existing guidelines.

The analysis conducted in this chapter provided means for development of InSiM with respect to the disaster management domain.

Chapter 5

Collection of Experimental Data

5.1 Introduction

The SSM analysis presented in the previous chapter revealed that incident commanders do not currently consider the behaviour of the general public when deciding on the most appropriate locations of the cordon zones. However, it was identified that anticipating human reaction and consequently incorporating such information into the decision making processes could potentially speed up and improve procedures associated with principles of protection.

The scope of this chapter is to collect empirical data regarding behaviour of people after a CBRN explosion. These data are used in subsequent chapters for obtaining information based on which behaviour of agents in InSiM is defined. As identified in Chapter 3 the nature of the problem suggests that a qualitative approach to data collection would be more appropriate. This is due to the limited availability of desired information at a sufficient level of detail on which to base the design of the model.

The qualitative data collection methods are inevitably biased towards the opinion of the researcher who designed and conducted the experiments, and analysed the obtained data. This is because the structure of the experiment partly reflects his/her understanding of the discussed problem or situation (Holliday, 2007). Therefore, the approach presented in this chapter is biased by inevitable personal judgement.

The structure of the chapter is as follows. A brief review of the scientific literature describing human behaviour in emergencies is provided in Section 5.2. The findings of the review help to scope the leading questions of the two experimental studies. The organisational matters of the experiments and the approach adopted for recording the participants' responses are described in Section 5.3. To gain understanding of the human behaviour from more than one perspective two different qualitative techniques are used: semi-structured interviews (SSI) and photo elicitation interviews (PEI). These methods are further explained in Sections 5.4 and 5.5. Four pilot studies were conducted by which the proposed methods were tested (see Section 5.6). Section 5.7 describes the population sample selected for the empirical research. The limitations of the selected data collection approach are discussed in Section 5.8. Section 5.9 briefly outlines the use of the collected data in the subsequent methodological steps.

5.2 Human Behaviour in Emergencies

Perry and Lindell (2003) argued that some of the policy makers and planners believe that people respond to disasters in disorganised and personally disoriented manner which is characterised by panic. However, existing studies have repeatedly demonstrated that panic or self-preservative aggression are not a common reaction (Alexander and Klein, 2005; Sime, 1999; Mawson, 2005).

Figure 5.1 presents a theoretical framework of human reasoning in emergencies. This framework is based on findings from scientific literature published by psychology, sociology, and human factor experts. The framework aims to capture the most common human response to a CBRN incident. Drury (2004)

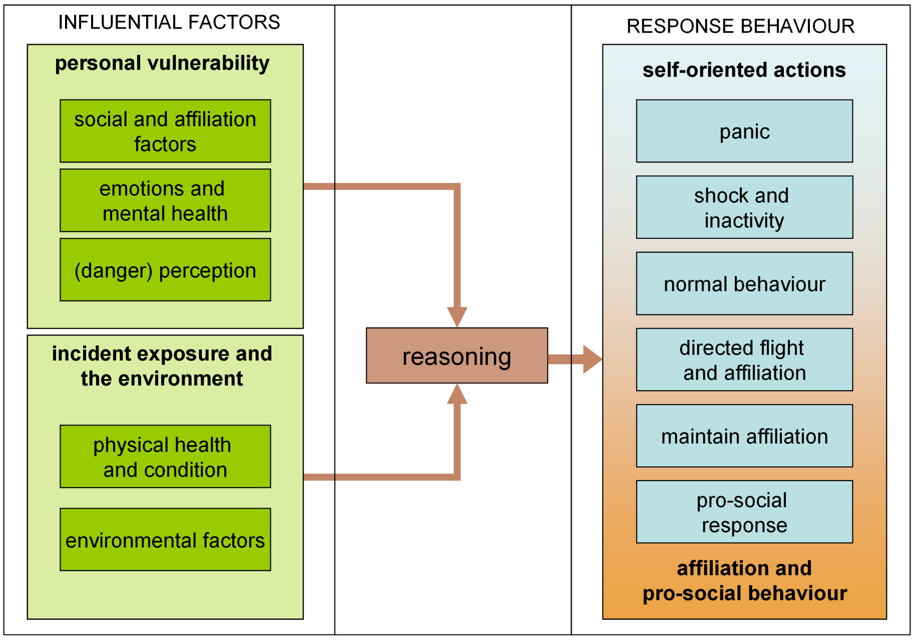

Figure 5.1: Theoretical framework of human reasoning in emergencies.

argued that similar types of behavioural patterns can be detected across different scenarios, disasters and with a different population of survivors. Therefore the theoretical framework is constructed with use of publications reporting response to any type of sudden, impulsive and location restricted emergency. Each component of the framework is described in greater detail in the following paragraphs.

The initial reaction to an explosion was reported to be a shock caused by the extreme level of stress and fear. The shock however only persists for a short period of time (Alexander and Klein, 2006; Tyhurst, 1957). After the initial shock had eased, the majority of people expressed a strong need of togetherness (Drury, 2004; Helsloot and Ruitenberg, 2004). Based on comparative interviews of survivors from eleven different emergencies, Drury and Cocking (2007) reported that victims often formed groups driven by a need of contemplating with others on what just happened (*Maintain affiliation* component of the theoretical framework). Beside creation of the ad-hoc relations people also sought the proximity of familiar persons and places which were perceived as safe (Mawson, 2005).

This is represented by the *Direct flight and affiliation* component of the framework. It was also identified that following the impact, uninjured victims were often the first to search for survivors and to care for the injured, using whatever resources available to improve the situation (Perry and Lindell, 2003) (*Pro-social response* component).

Analysis of the July 7th London bombings conducted by Drury and Cocking (2007) showed evidence of self-sacrifice of some people for sake of helping others. The reviewed literature also revealed that panic has been occasionally reported but only when individuals felt trapped, vulnerable and helpless (Mawson, 2005; Perry and Lindell, 2003). Panic flight seemed to involve a relatively small proportion of the population exposed to the threat and usually did not persist for a long period of time (Quarantelli, 1954). The depicted behaviours are in the framework organised around two extremes: self-oriented actions and affiliation and pro-social behaviour.

Alexander and Klein (2006) claimed that the response action preformed by each individual was influenced by four distinct factors: emotions (victim's immediate feelings), cognitive factors (level of confusion and perception of the situation), social factor (reaction to others) and physical aspect (health and physical condition of the individual). A more specific list of such factors was provided by Still (2000) who argued that the behaviour is influenced by communication skills of the individual, his/her mobility, social affinity, alertness, role position in the society, commitment, focal points, familiarity with the area, visibility and characteristics of the environment. In the theoretical framework the factors were summarised into two groups: (i) *Personal vulnerability* which is dependent on personal characteristics of individuals and (ii) effects of the explosion and the environment, i.e. *External factors*.

It has been reported that despite the physical nature of the area people tend to evacuate in the direction of their homes or place where their family is located by following well-known paths as opposed to searching for alternative routes (Dymon and Winter, 1993; Raphael, 2005; Mawson, 2005). Nevertheless, more detailed information on what characteristics of the environment have the strongest effect and how exactly they affect the response behaviour has not been discussed. In addition, the spatial behaviour is usually studied within closed environments such as stadiums (see Still, 2000), planes (see Court et al., 2004) or buildings (see Ali and Moulin, 2005).

It is expected that the findings of the two experimental studies discussed in the following sections will reveal the same behaviours as described in the theoretical framework. Nevertheless, due to the lack of understanding the effects of the external factors on the human behaviour it is necessary to focus the empirical research towards collection of such information. In this project two experimental studies are setup to gain insight into these issues. The selected data collection approach is further discussed in the following sections.

5.3 Organisation of the Empirical Research

In order to minimise the time participants had to reserve for the study, it was decided to conduct the experiments in locations familiar to the interviewees. It is believed that this resulted in more focussed attention during the experiments. In addition, each interview was conducted in privacy.

The experiment was tape-recorded to capture all details of the conversation. The recording also made the experiment more fluent since no pauses needed to be made to write down the answers.

To be able to put the answers into perspective, a short questionnaire was designed (see Appendix C) to collect basic demographic characteristics of the participants and their knowledge of the areas represented on the photographs used in the PEI. This information was used during analysis of the data in subsequent chapters.

The experiments were conducted in the following order:

1. The participant was introduced to the aim of the study.
2. The participant was asked to sign a written consent to confirm understanding of the study, his/her rights and the use of the collected information in subsequent research (see Appendix D).
3. The short questionnaire was filled in by the participant.
4. Collection of data through SSI commencing with a short explanation of the use case scenario around which the questions of the interview were formed.
5. Collection of data through PEI commencing with a short explanation of the use case scenario according to which the participants ordered and subsequently discussed the provided photographs.

5.4 Semi-structured Interviews

At the beginning of the interview the following scenario was presented to the participants to outline the situation around which the consequent discussion was formed:

> *Imagine that you are walking in a centre of a city and suddenly you hear a massive explosion. You are instantly hit by a shock wave from the blast. The flying debris hits your arm but the injuries are not severe and don't obstruct your movement in any way.*

Before the leading questions for the SSI were identified, it was necessary to obtain additional knowledge about human behaviour in emergencies. Analysis of scientific literature revealed that similar patterns of response have been identified across different incident scenarios (see Karasová and Lawson, 2008). The behaviours range from purely self-oriented actions such as panic, shock or evacuation, to pro-social behaviour characterised by helping others. The behaviour is determined by the individual's psychological state which is represented by feelings (fear, pressure, entrapment, confusion, etc.), and movement (uncontrolled run, directed flight, staying in place, etc.; Perry and Lindell, 2003; Drury and Cocking, 2007; Quarantelli, 1954).

Therefore, the principal questions, which remained the same for all the experiments, are formulated in such a way which enables collection of information regarding each of these components separately. The questions are:

- What do you think your first reaction would be?
- How would you feel?
- Why would you feel that way?
- Would you move anywhere?
- Why do you think you would move that way?
- What would you do next?
- Why would you do that?
- What factors would influence your reaction?
- How would they influence your reaction?

The questions were specifically formed in a very abstract manner to avoid explicit direction of answers and to provide an opportunity for interviewees to express whatever ideas first come into their minds. The term *factor* is used frequently in this thesis, especially in Chapters 6 and 7. A factor, as it is understood in this research, is an element that contributes to the final reactive behaviour of a person to the CBRN explosion. It is connected with a characteristic of the environment and persons' sense of place and space. Aspects that are associated with human physical or mental health (illness, disability, depression, etc.) are omitted. Although they have an influence on human reaction, their consideration would complicate the data collection and shift the focus of this research which predominantly concentrates on spatial aspects of human behaviour.

5.4.1 Aim of Semi-structured Interviews

The aim of the SSI is to gain general understanding of the situation ,i.e. identify how people would react during the specific type of emergency and what factors they would consider when deciding on what to do once the initial shock subsided. Hence the participants were encouraged to discuss a very broad range of considerations and issues without any particular focus.

5.5 Photo Elicitation Interviews

The second qualitative method used in the empirical study was a set of photo elicitation interviews (PEI) in which photographs were used to invoke comments and discussions related to the situation they depict (Banks, 2007). Each participant was given a collection of coloured A4-sized photographs depicting different areas in the city centre (see Section 5.5.5 for further explanation). Participants were then asked to carefully assess each photograph and arrange them according to their preference of selecting the particular location it represents as an evacuation route from an incident site. The experiment concluded with a discussion during which the participants were encouraged to specify what factors influenced their decision in arranging the photographs in that particular way. With respect to recommendations for card sorting research that inspired the definition of the PEI approach (Banks, 2007), each collection contained six photographs.

5.5.1 Aim of Photo Elicitation Interviews

The aim of the PEI was narrower in focus than the SSI. This technique was directed towards identification of preferable evacuation routes from the incident site. The additional intention was to determine factors that influence such choice. Since the photographs represented real physical environments, a focus was put on discussing the participants' sense of place and space with respect to the area depicted in the photographs.

5.5.2 Collection of Photographs: The Approach

Terrorist attacks have usually been targeted towards areas with a high concentration of people (Home Office, 2004). Therefore, the use case for InSiM (described in depth in Chapter 8) represents a situation that depicts the centre of a city late morning on Saturday when it is full of shoppers. In order to collect data which are relevant to the use case, the photographs used in PEI depict different streets in the city centre during this time period (more is explained in the following text).

In some research projects the photographs were taken by the researcher (e.g. Epstein, 1999) whereas in others the participants were encouraged to either bring their own photographs (e.g. Loeffler, 2004) or were given an opportunity to take representative pictures as part of the study itself (e.g. Smith, 1984).

In this research, the presented photographs were taken by the researcher prior to the experimental studies. Such approach was selected for the two following reasons. First, the intention was to show participants photographs that represent unfamiliar locations. Hence, the knowledge of the depicted area was recorded prior each interview.

Secondly, to be able to identify how different environments influence the decision, it was found necessary to depict on the photographs situations as diverse as possible. It was already highlighted that current psychology, sociology and human factor studies do not concentrate on identification of environmental factors affecting human reasoning under emergency conditions. Therefore, it is not possible to *a priori* determine what exactly the term *diversity* with respect to the environment represents. The diversity was in this research understood with regard to the (i) number of people on the street, (ii) openness of the area (width of the street, height of the buildings, green spaces, etc.), (iii) parked or moving traffic, and (iv) shops . The listed characteristics were determined according to what the author would find important if she participated in these experiments. This influenced the collected information since the structure of the experiment was biased towards the researcher's perspective and understanding of the situation.

5.5.3 Collection of Photographs: The Process

The photographic material was taken in Nottingham and Leicester. These are the same cities in which the experiments were conducted (see Section 5.7). In addition, the centres of these two cities also form the simulation environment of InSiM (see Section 7.2).

Selecting two cities rather than one was because:

- Selection of participants from the same geographical location would provide data capturing the situation only from a perspective of one particular city.
- The photographs can represent both familiar and unfamiliar locations.
- It enables us to identify whether the reaction is dependent on the particular city (depicted on the photograph);
- It provides a means for testing the transparency of InSiM in respect of

utilisation of different datasets for definition of the simulation space (discussed further in Chapter 8).

The reasons for selection of these two specific cities were:

Population: With respect to population Nottingham and Leicester represent average-sized British cities (based on comparison of all 66 British large towns officially accredited with city status (listed in UK Cities, 2009); data collected from UK Census 2001) with similar population size (Nottingham 285,000; Leicester 280,000).

Layout of the centre: Both of the cities have large shopping centres located in the city centre attracting large number of visitors during shopping hours (Nottingham - Victoria, Leicester - Highcross). In addition the layout of the centres is very similar; a mostly pedestrianised centre delimited by large busy streets often dual carriageways.

These similarities enable combination of the photographs without introduction of many differences, keeping the photographic material transparent. The photographs were taken on the same day (12th April 2008) over a period of 4 hours (approximately 10AM - 2PM). All photographs represent a snapshot taken from the centre of a street capturing its whole width together with the adjacent buildings. Hence, the represented areas are depicted from the same view. The locations of the photographs for Nottingham are shown in Appendix E and for Leicester in Appendix F. In total 60 photographs were acquired (30 in Nottingham and 30 in Leicester). However, not all of them were used in the experiments. For the sake of clarity the maps in the appendices only depict locations of 20 photographs that were applied to the PEI.

Since large number of streets in the Leicester city centre were under renovation (replacement with new surface), and due to the construction works on the new Highcross shopping centre (opened for the public 4th September 2008; BBC Leicester, 2009), the photographs in Leicester were mainly collected in the area between the Clock Tower and the railway station. In Nottingham the photographs were taken to cover the whole area of the city centre.

5.5.4 Organisation of Photographs

Out of the 60 acquired photographs only 20 (12 Nottingham, 8 Leicester) were selected as suitable for the needs of the research. The remaining 40 were discarded due to one or more of the following reasons: (i) similar situation depicted on another photograph; (ii) same location as on another photograph but taken from different place and angle; (iii) photograph is of a poor quality (dark, light, blurred, did not depict the whole width of the street, etc.) (iv) the road is obstructed by road works (Leicester only).

Seven thematic categories were defined with respect to the *diversity* as specified on page 131. The intention was to create categories that represent different areas of the city centre. Nevertheless, since the definition of diversity was based on the researcher's own understanding of what such term represents (with respect to the emergency situation), the specification of the categories is subjective. Similarly, the organisation of the photographs into the categories was biased by the researcher's own judgement. The categories are:

- **Dual carriageway:** is a road in which two directions of traffic are separated by a central barrier or strip of land (Department for Transport, 2009). In Nottingham and Leicester these roads delimit the centre of the city. The road is usually very wide and is full of fast-moving traffic, with minimum numbers of people and shops.
- **Pedestrianised "high street":** an area where vehicular traffic is prohibited (Department for Transport, 2009). Regarding the two cities these areas contain large number of people and shops. The width of the street can vary depending on the layout of the city.
- **Main road A:** is a single carriageway which serves for vehicular access

	Category						
	Dual c-way	Pedestr. "high street"	Main road A	Main road B	Side streets	Common street A	Common street B
Photograph	22N 26N 3L	2N 5N 25N	1N 33N 12L 13L	2L	16N 17N 5L	10N 4L 6L	13N 28N 9L

Table 5.1: Thematic categorisation of photographs.

from and to the city centre. These streets are surrounded with relatively high buildings (three and more storeys). They are not very busy with pedestrians and contain only a limited number of shops.

- **Main road B:** is a single carriageway with wide pavements surrounded by lower buildings (up to 3 storeys), parks, or open spaces (e.g. square).
- **Side street:** is narrow often with cars parked on the side. These are streets which are very common in the city centre of Nottingham and Leicester. They connect the busy shopping areas with the outskirts of the centre. They are usually neither busy with traffic nor with pedestrians.
- **Common street A:** is fairly wide containing several shops and parked cars on the side. They are not as busy with traffic as *Main roads A and B* and contain more pedestrians than a *Side street*.
- **Common street B:** is similar to definition of *Common street A* but doesn't contain any shops.

The organisation of the 20 selected photographs with respect to these categories is depicted in Table 5.1. The corresponding photographs are shown in Appendix G. Each photograph is associated with a unique ID which starts with its order in the original collection of 60 photographs where both cities started with photograph 1. The number is followed by an identifer representing *N* (Nottingham) or *L* (Leicester).

The majority of the categories contain three photographs which represent both of the cities. Due to the road works in Leicester, it was not possible to fully capture some of the areas (the *Pedestrianised "high streets"* in particular). Therefore, this category consists only of photographs from Nottingham. Category *Main road B* contains only one photograph *2L*. Although several other photographs of similar places were taken, they were not representative enough to appropriately illustrate the situation. Nevertheless, this situation was not found as very common in both of the cities.

5.5.5 Creation of Photographic Collections

The categories presented in the previous section served as the basis for the creation of eight photographic collections (A-H) that were used during the PEI. Each collection comprised a set of six distinct photographs each taken from a different category (e.g. *Pedestrianised "high streets"*, *Main road A*). The collections were created to include photographs of one city only (*B,D,E*), or a combination of both cities (*A,C,F,G,H*). This enabled the testing of what would guide a participant's decision in unfamiliar environments and how local knowledge influences the assessment of the photographic preferences. The summary of the photographs assigned in each collection is presented in Table 5.2.

Since the difference between the two categories representing *Common street A* and *B* is very small (only distinguished by shops), it was decided to create some categories with only one of them. The eliminated photograph was then replaced with *Main road B*. Even though *Main road B* streets were not widely represented in either of the cities, for the sake of completeness, it was decided to include them in the study. Finally, the photographs were presented to the participants at the same time under ID's (*Photo 1-6*) that were randomly assigned prior to the experiments (Table 5.3).

Collection	Photographs						
	Dual c-way	Pedestr. "high street"	Main road A	Main road B	Side streets	Common street A	Common street B
A	22N	5N	33N	2L	5L	6L	
B	26N	5N	33N		16N	10N	13N
C	22N	2N	13L		17N	10N	9L
D	3L	25N	12L	2L	5L	4L	
E	3L	25N	12L		5L	6L	9L
F	3L	25N	12L		5L	6L	28N
G	22N	2N	1N		5L	4L	28N
H	3L	5N	13L	2L	16N	4L	

Table 5.2: Photographic collections for PEI experiments.

Collection	Photographs					
	Photo 1	Photo 2	Photo 3	Photo 4	Photo 5	Photo 6
A	6L	22N	5N	33N	5L	2L
B	26N	10N	33N	13N	5N	16N
C	13L	10N	22N	2N	9L	17N
D	12L	2L	3L	25N	4L	5L
E	12L	5L	3L	25N	6L	9L
F	12L	5L	3L	25N	6L	28N
G	1N	5L	22N	2N	28N	4L
H	13L	2L	3L	5N	4L	16N

Table 5.3: ID of the photographs in PEI collections.

5.6 Pilot Studies

Pilot studies with four participants were conducted to test and refine the structure of both interviewing methods. The aim of the pilot studies was to ensure that the questions were logical and understandable for the participants and to identify how much time was needed per experiment (Fox, 2006). The leading questions of the SSI were, after the first two pilots, reformulated into more specific form which was subsequently tested in the following two pilots. This form remained the same for the rest of the experiments. Hence, the data collected in the later two pilots (participants *P3, P4*) were also included in the analysis reported in Chapter 6 .

5.7 Participants

To capture the heterogeneity of people which can be present in a city centre at the time of an explosion the ideal population sample should represent people with diverse social settings, age and different local knowledge of the area under study. To obtain an understanding of the behaviour with respect to these diverse demographic characteristics at the same level, the proportion of the population sample should be ideally equally distributed.

The aim of this thesis is to propose, test, and assess a methodology for development of geo-simulation models that incorporate real-life information. The intention of the experimental studies was to demonstrate how part of this information can be collected. Therefore, for the sake of simplicity, it was decided to conduct the experimental studies with participants that were easily approachable. The selection was limited to Nottingham university staff, students, friends and their friends. In addition, an email was sent to mailing lists at Leicester University, though with no response. Therefore, it was decided to contact people directly or through friends resulting in the Leicester population sample consisting of university staff and students (at both The University of Leicester and De Montfort University).

Both experiments were conducted with 22 people; 12 people from Nottingham, 10 from Leicester. Altogether the data were collected from 24 participants including also the 2 pilot studies which took place in Nottingham. This indicates that the participants were not selected randomly. Hence, the acquired information is biased towards a certain population group. This fact is reflected in the geo-simulation outcomes which need to be assessed with respect to that particular selection of people and should not be generalised to the whole population.

All Leicester studies were completed on the same day. In Nottingham the experiments were conducted within a period of two weeks. The pie-charts in

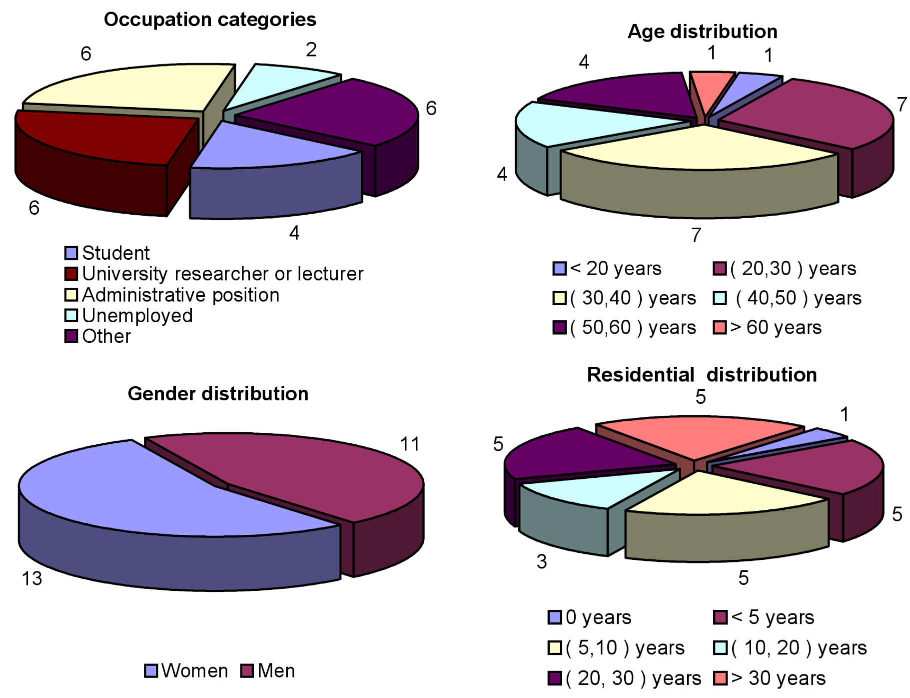

Figure 5.2: Characteristics of the population sample.

Figure 5.2 present proportions of the population sample in relation to occupation, age distribution, gender and years of residence in the studied areas.

A unique ID number was assigned to each participant prior to the interviews. The number commences with a letter representing the location of the interview (*N* - Nottingham, *L* - Leicester) followed by a number representing the order in which the people were originally contacted. Two participants (*N04*, *L01*) cancelled at the last minute. However, since the order was created in advance, these ID numbers were not replaced.

5.7.1 Distribution of Photographic Collections

In order to avoid further biases in the experiments, specifically those caused by presenting a single collection to the whole population sample, it was decided to use all, i.e *A*-*H* collections. Each participant was given one collection. Since it was not possible to identify which collections are more representative than others, and how familiar the participant is with the photographed areas, the

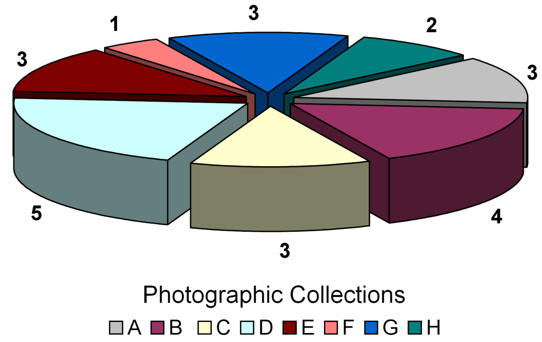

Figure 5.3: Distribution of photographic collections among participants.

selection was always determined as the first step of the PEI. The intention was to distribute the collections evenly to eliminate biases connected with specific areas. The final allocation of the collections among the population sample is shown in Table 5.4 and graphically represented as a pie-chart in Figure 5.3.

The collections were distributed to represent three types of situations regarding familiarity of the participants with the locations as follows:

- photographs depicting both familiar and unfamiliar city (participants *P3*, *P4*, *N02*, *N06*, *N08*, *L03*, *L04*, *L05*, *L07*, *L08*, *L10*, *L11*);
- photographs of the familiar city only (participants *N01*, *N03*, *N09*, *N11*, *L02*, *L06*, *L09*);
- photographs of the unfamiliar city only (participants *N05*, *N07*, *N10*, *N12*, *N13*).

The photographic collections should have ideally been distributed equally to avoid further bias. However, since some of the participants were familiar with both cities, it was not possible to keep the distribution as planned. This is reflected by larger number of participants that were presented collections with both familiar and unfamiliar cities (12 participants).

Pearson's Chi-square test was applied to determine, whether the observed distribution was significantly different from the expected one. The calculated value $\chi^2 = 3.25$ is smaller than the critical value at 0.05 significance level for 2 degrees of freedom ($\chi^2_{crit} = 5.99$). Hence, the null hypothesis cannot be rejected. This means, that the difference between the expected and observed distribution is not, with respect to the population sample, statistically significant.

5.8 Limitations of the Data Collection Approach

The literature review (Section 5.2) provided a good opportunity for the collection of diverse research results and critical points of current knowledge of human response to an emergency. It was identified that similar response patterns have been observed across a range of different emergency scenarios. The collection of such information is crucial for validating results of the experimental studies.

Experimental research is a good method of collecting information from the perspective of the affected people. However, the accuracy of the collected data is dependent on the experience of the interviewed population sample with the studied situation. The most accurate source of information would be direct interviews with disaster survivors or review of archives containing victims' testimonies and observation reports. These sources would need to be consulted should the geo-simulation model be used for prediction purposes.

Since the InSiM prototype is meant to be developed for testing the proposed methodology it was found appropriate to interview people who have no experience with any explosion related incidents. Although the collected information might not be accurate, it is sufficient to proof the concept of using qualitative research techniques to collect information regarding behaviour of a system which is to be modelled by an agent-based simulation. Nevertheless, utilisation of the results of the experimental studies as well as findings of the simulation should be assessed with caution since they may lead to incorrect interpretation of hu-

Participant	P3	P4										
Collection	A	A										
Participant	N01	N02	N03	N05	N06	N07	N08	N09	N10	N11	N12	N13
Collection	B	C	B	D	C	D	C	B	D	B	D	D
Participant	L02	L03	L04	L05	L06	L07	L08	L09	L10	L11		
Collection	E	G	H	G	E	A	F	E	G	H		

Table 5.4: Distribution of photographic collections among participants.

man behaviour, which could in turn produce catastrophic consequences if consulted during the creation of evacuation plans.

5.9 Summary

This chapter outlined the approach that was followed to collect empirical data. Two methods, semi-structured interviews and photo elicitation interviews, were applied to obtain two different perspectives on human response to an urban CBRN explosion. Due to the qualitative nature of the experiments their structure, and consequently the nature of the collected data, to a large degree reflects the attitude and understanding of the researcher to the studied phenomenon.

The experimental data are further analysed in the next chapter to identify how people react, what influences their decision on where to go, and what route they follow. In order to identify whether the size of the population sample was sufficient, data saturation (Guest et al., 2006) was conducted as a part of the analysis to identify to what extent new information was obtained in every interview. The generated information is subsequently used for the definition of InSiM parameters, the behavioural algorithms of agents (Chapter 7), and for its final validation (Chapter 9).

Chapter 6

Analysis of Experimental Data

6.1 Introduction

This chapter focuses on analysis of the data collected by the two experimental studies introduced in the previous chapter. The data have been organised into two data sets:

- SSI dataset: data generated by the set of semi-structured interviews;
- PEI dataset: data generated by the set of photo elicitation interviews.

The general aim of the analysis is to identify and summarise the most common behaviour that people would adopt after experiencing a CBRN explosion. In addition, the focus is put on identification of factors (as defined on page 129) that influence human decisions in such an emergency situation.

The remaining sections of this chapter are organised as follows. Section 6.2 lists aims guiding the selection of the analytical methods adopted for the processing of the collected data. The participants are then divided into three demographic categories by which the data are further explored (Section 6.3). The subsequent section (6.4) describes the adopted analytical approach. The results of the analysis are discussed with respect to the list of aims in Section 6.5 and the findings are summarised in Section 6.6.

6.2 Aims

The selection of the most appropriate analytical techniques to extract the required information from the two datasets is directed by the following aims:

Aim 1: Identify the most common response behaviours to the CBRN explosion.

Aim 2: Identify what are the preferred destinations towards which people would proceed.

Aim 3: Identify factors that influence human decision during emergency situations and their effects.

Aim 4: Identify whether similarities exist between results generated by analysis of the SSI and PEI datasets.

Aim 5: Determine whether the findings of the experimental studies can be generalised.

6.3 Demographic Categories

In order to identify whether demographic background has an impact on the findings the population sample was divided into three demographic categories with respect to:

- **location**: different geographic locations of the population sample; determined by the city where the interview was conducted (*Nottingham participants*, *Leicester participants*);
- **gender** (*female participants*, *male participants*);
- **age**: for easier manipulation with the data the sample population was divided into two age categories delimited by the mean age ($\bar{x}$ = 38 years) rounded to the closest factor of ten ($<$ *40 years participants*, $\geq$ *40 years participants*).

6.4 Analytical Approach

The techniques used for processing the empirical data can be grouped into three categories according to the adopted analytical approach:

- **qualitative analysis**: interpreting and categorising the data to determine contextual patterns (specified in Section 6.4.1);
- **quantitative analysis**: describing the main findings in quantitative terms (specified in Section 6.4.2);
- **data saturation**: evaluating whether a sufficient number of experiments was conducted (specified in Section 6.4.3).

6.4.1 Qualitative Analysis

6.4.1.1 Content Analysis

Content Analysis (CA) is applied to identify coherent patterns in the material collected by the two experimental studies. This technique is associated with a systematic search for quotations or observations that are connected with the same underlying idea or concept (Patton, 1987; Sommer and Sommer, 1991). The process consists of several steps which enable coding and classification of the data into categories that evolve from the collected material and have a meaningful context for the purposes of the research (Patton, 1987; Fielding and Raymond, 1998). According to Hancock (1998) the steps of the analysis are as follows:

1. Transcribe the recorded material.
2. Read through the transcript and highlight interesting or relevant information.
3. Make a list of the different types of detected information.

4. Organise the information into different categories according to the context of the information.
5. Identify relationships between the categories and if applicable reorganise them.
6. Iterate steps 2 - 5 until all relevant information can be assigned into one of the final categories.
7. Write down the definition or description of each category and provide examples from the transcript associated with the category.

In this research CA is used for extracting information from the records of the participants' answers during both SSI and PEI. The focus of the analysis is to identify the range of:

Aim 1: response behaviours;

Aim 2: preferred destinations;

Aim 3: factors guiding the decision on the selection of the evacuation route and their effects.

6.4.1.2 Qualitative Evaluation

Due to the qualitative nature of the results obtained by the CA, use of statistics for their assessment is limited. Instead, the findings can be compared and contrasted with use of qualitative evaluation of their similarities and differences. Such analysis enables discovery of emerging patterns that were not, prior to the data collection, known. In this research the findings of the qualitative evaluation are used as primary information based on which the characteristics of an agent in InSiM are defined.

Small frequencies of participants with respect to the demographic categories challenge use of statistics to formally assess the significance of the differences.

As the frequencies in several categories are often less than 5, both rules of thumb for application of Pearson's Chi-square test are violated [1]. Therefore, the distribution of the interviewed population sample among the categories is assessed qualitatively, by reporting the extent of the differences. Due to the qualitative origin, the findings of the analysis reflect the researcher's interpretation of the collected data and should not be generalised without taking additional measures for assessing their validity.

In this research the qualitative evaluation is used for comparing distributions of the different demographic categories with respect to the identified:

Aim 1: response behaviours,

Aim 2: preferred destinations,

Aim 3: factors guiding selection of the evacuation route.

A qualitative approach is also used for assessing whether similar factors were identified in both experimental studies (**Aim 4**). The findings of such analysis reveal whether the collected information is independent of the applied data collection approach.

6.4.2 Quantitative Analysis

6.4.2.1 Contingency Table

Although the empirical data were collected with use of qualitative techniques, the material can be partly quantified. This involves interpretation of the textual information through numbers (Bernard, 1996). Such approach results in more formal organisation of the qualitative data providing means for their comparison. To be able to obtain basic descriptive statistics about the interviewed population sample, the data need to be transformed into a matrix. This matrix is

[1] Rules of thumb for Pearson's Chi-square test: (1) "If the number of categories is greater than 2, no more than 1/5 of the expected frequencies should be less than 5, and certainly none should be less than 1"; (2) "If the number of categories is 2, both the expected frequencies should be 5 or larger." (cited from Ebdon, 1985, pg. 67)

represented by a *contingency table* expressing the relationship between values of a specific category identified by the CA (columns) and their distributions among the population sample (rows).

Contingency tables are created to summarise the following data:

Aim 1: proportions of the population sample with respect to the response behaviour categories;

Aim 2: proportions of the population sample with respect to the identified preferred destinations;

Aim 3: distribution of the population sample among the factor categories from both SSI and PEI datasets;

6.4.2.2 Stacked Bar Chart

The data organised in the contingency tables are further summarised into a number of stacked bar charts to obtain additional quantitative insight into the two datasets. Such representation is used to describe the proportion of the categorical values. To better reflect the distribution, the stacked bar charts present the percentage of the sample rather than the actual frequencies as depicted in the contingency tables.

Since the proportions of the population sample are not equal (with respect to the demographic categories), it is necessary to normalise the data. This results in representation of the data in a common scale allowing their easier assessment. The data are normalised according to Equation 6.4.1,

$$a_n = \frac{a \cdot c}{(a + b)} \tag{6.4.1}$$

where a and b correspond to the percentage of the proportion within the demographic group (e.g. *Nottingham participants* and *Leicester participants*). Variable

c depicts the total percentage of the specific category (e.g. *home* as one of the preferred destinations) with respect to the whole population sample (all 24 participants). For example, 46 % (11) of the participants reported that *home* is their preferred destination; out of this proportion 29 % were from Nottingham and 70 % from Leicester. By applying Equation 6.4.1, the proportion of *Nottingham participants* depicted in the stacked bar chart is normalised to 13 % of the total population sample ($Notts_n = \frac{29 \cdot 46}{(29+70)} = 13$).

Stacked bar charts are created to graphically represent the distribution of the same data that were organised into the contingency tables.

6.4.3 Data Saturation

In order to achieve stability in the collected information an appropriate sample size should be determined. Guest et al. (2006) suggests that the sample size relies on a concept of saturation, or the point at which no new information or themes are observed in the data. In this research, the most appropriate sample size can only be identified implicitly, i.e. after analysing the collected data. Additional participants need to be interviewed if the completed studies do not reach saturation. The saturation is expressed by a function depicting cumulative frequency. The following findings are tested for data saturation:

- categories of identified response behaviour;
- categories of identified preferred destinations;
- categories of factors identified from both datasets;

The outcomes of the data saturation analysis are also used to support evaluation whether the findings of the experimental studies can be further generalised to the whole population (**Aim 5**).

6.5 Results

The overall length of the recorded material depicting both experimental studies is approximately 200 minutes. The average time spent with a participant was 25 minutes, where the first 5 minutes covered the explanation of the experiments and their aims. The semi-structured interview and the photo elicitation interview took a similar time which was on average 10 minutes per experiment. The transcripts of the data collected in both experiments are grouped into two datasets (SSI and PEI) amounting to approximately 30,300 words. The following sections provide the results of the applied methodology organised according to the aims of the analysis.

6.5.1 Aim 1: Response Behaviour

This aim was addressed by CA of the SSI dataset. All together three response behaviours were identified:

- **Assistance** by providing help to those who need it. In addition to the injured this also apply to those who would be in shock and distressed, or those who are not familiar with the area and would be seeking advice on directions. It was discovered that participants who have passed a first aid course would feel obliged to help the injured although they were not confident about the usefulness of their aid in such circumstances. In case of danger, people would try to move the injured away to safer places. However, if the person is injured more severely they would remain in place until professional medical help arrived.
- **Evacuation** from the incident area due to the perceived level of danger.
- **Shock** due to the sudden and unexpected nature of the CBRN explosion. One of the previous two response behaviours would be adopted after the initial shock subsides.

The comments of the participants based on which the above categorisation was made are provided in Table 6.1.

	Assistance
P03	*"I think my initial reaction would be to help somebody next to me who was injured or somebody in distress."*
N02	*"If somebody need help, I would find it very difficult to leave them. If there were people trying to get away, I might try to say, I know where I was going, I know the area, come with me and try to get to some open space."*
N03	*"I would look around if something needs to be done, if someone else needs to be taken to a hospital."*
N05	*"I would immediately look my surroundings and see if there were any other people near by injured. I have done the first aid course, I might be able to assist."*
N06	*"My first reaction upon checking myself and then would be to look around and see if anybody needs help."*
N08	*"I feel like I would try to help people around me."*
N11	*"You get both, feeling of wanted to go and have a look and to see what's happened, but in the same time you want to run away to safety. You want to be helpful or you just want to see, because that's kind of human nature....I am the first aider so I should go and help casualties, whether or not you volunteer yourself obviously depends on what you find."*
N12	*"I have a first aid course so I would try to help."*
L06	*"I would look and see whether I could help, I think."*
	Evacuation
N01	*"Obviously I would try to move out of that area."*
N07	*"Run away!"*
N09	*"I look around, assess where the masses of people are, and move away."*
N10	*"Assuming that the bomb had gone off in ahead of me, I would probably turn around and retrace my steps. If it went off behind me, I would want to continue in the direction I would be going. "*
N13	*"I think the first reaction would be to just run away."*
L04	*"If I am not seriously injured, to get as far away as possible."*
L05	*"I would probably try to get away from the scene as quickly as possible."*
L07	*"I would try to walk away from it."*
L10	*"I would look to see where the blast have come from, and look to see if there is anymore possible danger which I would try to avoid."*
	Shock
P4	*"The first reaction would be a shock. And then, I would try to move, because you know something happened at that place, you have to try to move to some safer place."*
L02	*"I think it would probably take a while to realise what has actually happened ... I think you have to take into account what's happened and where it's happened before you move to assess the situation."*
L03	*"I imagine I would be taken by surprise and then I would try to leave the area."*
L08	*"I would probably be shocked from what has happened. Then I would try to make sure I was not in any immediate danger from anything else falling off or falling down."*
L09	*"I would be definitely shocked of what has happened. And I guess I would be trying to work out what have happened, what I should be doing, where I should go."*
L11	*"Obviously a bomb goes off so, you are sort of anxious. So, I would try to get maybe to a side street and try to think what I am going to do next."*

Table 6.1: Response behaviour to the CBRN explosion.

Location	Participant	Age	Gender		Response behaviour		
			Female	Male	Assistance	Evacuation	Shock
Nottingham	P3	69	1		1		
	P4	32		1			1
	N01	39	1			1	
	N02	36	1		1		
	N03	33	1		1		
	N05	26		1	1		
	N06	40		1	1		
	N07	35	1			1	
	N08	43	1		1		
	N09	59	1			1	
	N10	58		1		1	
	N11	28	1		1		
	N12	29		1	1		
	N13	42	1			1	
Leicester	L02	52	1				1
	L03	51		1			1
	L04	38	1			1	
	L05	30		1		1	
	L06	45		1	1		
	L07	34	1			1	
	L08	23		1			1
	L09	23	1				1
	L10	21		1		1	
	L11	19		1			1
Total			13	11	9	9	6

Table 6.2: Demographic characteristics of the total sample and its distribution with respect to response behaviours.

Information regarding the response behaviour is quantitatively summarised into the contingency table (Table 6.2). In addition, the table also includes demographic information characterising each participant.

The contingency table is further used for calculating proportions of response behaviour of the population sample with respect to its demographic characteristics. The results of the normalisation process are summarised in Table 6.3. This table also serves as an input of information for creation of the stacked bar charts which are depicted in Figure 6.1. The stacked bar charts illustrate that the two most common response behaviours (equally distributed among the population sample; 38 %) are *Assistance* to others and immediate *Evacuation* from

Category	Assistance	Evacuation	Shock
Total [%]	38	38	24
Nottingham [%]	57	36	7
Leicester [%]	10	40	50
Nottingham norm [%]	32	18	3
Leicester norm [%]	6	20	21
female [%]	39	46	15
male [%]	36	28	36
female norm [%]	20	24	7
male norm [%]	18	14	17
< 40 years [%]	33	40	27
$\geq$ 40 years [%]	44	33	23
< 40 years norm [%]	17	20	13
$\geq$ 40 years norm [%]	21	18	11

Table 6.3: Distribution of response behaviours with respect to demographic categories and results of data normalisation applied to SSI dataset.

the incident area. These two behaviours represent opposite reactions. Assistance demonstrates a highly pro-social approach leading in some cases to self-sacrifice for the sake of helping others (longer exposure to the CBRN substance dispersed by the explosion). In contrast, evacuation represents a self-oriented behaviour. The analysis revealed that 24 % of the participants would be in *Shock*. However, the shock would only persist for a short period of time. Once the shock subsides one of the two referenced behaviours would be adopted.

With respect to the different demographic categories *Assistance* would be provided predominantly by *Nottingham* participants while a large proportion of *Leicester* participants reported that they would be in *Shock* (Figure 6.1 a)). This notable difference could be a consequence of changes in the interviewing approach e.g. unintentionally directing the participant's answers. However, it could also reflect an existing trend emerging from social, political and cultural difference between the two cities. The *Evacuation* behaviour is almost equally distributed between the two cities. Almost equal distribution of the response behaviours can also be observed with respect to the gender and age of the population sample (Figure 6.1 b) and c)).

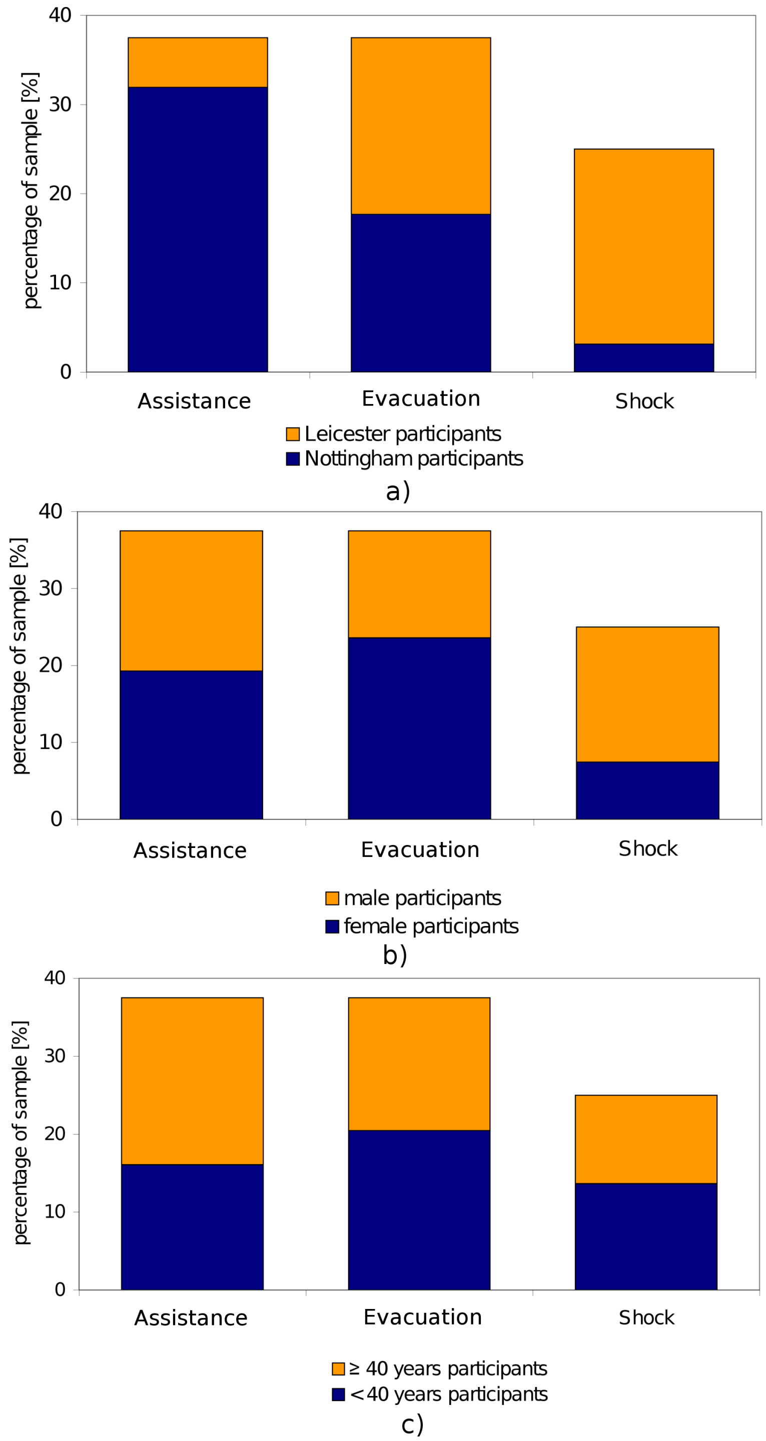

Figure 6.1: Distribution of response behaviours with respect to different demographic categories.

6.5.2 Aim 2: Preferred Destinations

The CA of the SSI dataset revealed three preferred destinations towards which the participants would navigate:

- **Home**, because it provides the feeling of safety and assurance. Moreover, home was also referred to as the place where family, partners, or friends would meet and discuss the situation.
- **Open space** near the incident but in a safe distance from the immediate danger. This destination was often associated with squares, parks, or wide pedestrian areas which are accessible and are not surrounded by high buildings. It was reported that people would expect response services to come to these places and give them advice, information and help.
- **Incident area**, which is the immediate area of the explosion. Two very diverse reasons for selecting such destination were reported: (i) to provide immediate help to the victims and (ii) curiosity and desire to observe the unusual situation.

Table 6.4 contains the answers of the participants with respect to the selection of the preferred destinations.

	Home
N01	*"I imagine I would move as directly away as I could, then I would look for a way home."*
N02	*"Well, I would think how can I get out of here and go towards home."*
N05	*"I would not walk towards the scene. I would probably walk towards a bus station or get a taxi or towards my car."*
N10	*"In the beginning I would walk just further away before thinking about where I wanted to go, and then I would try to get to my car."*
L02	*"Theoretically, I would go back towards home because that would be the safest way I can see out."*
L03	*"During an ordinary day I would try to get home or back to where I am working depending on where I have come from."*
L04	*"If I was in Leicester, I would probably come back here to work, because I could not walk home because I'd need a car. So, I would come here, but not to the building, just to get the car."*
L07	*"I think I would try to walk away from it and try to get home or to the train station, or something, if that was accessible."*

Continued on Next Page…

L08	*"I would go back home or somewhere where I won't be in danger."*
L09	*"I think at the beginning I would go any direction that would be out of the centre, and then probably come back home, because it's a residential area."*
L10	*"I would try and head in the opposite direction, and towards home, really."*
	Open space
P04	*"I would think maybe towards an open space, some safer area."*
N03	*"I would not like to walk towards the bomb. I would like to go somewhere safe, out of the city."*
N06	*"I would try to move away from the incident to same safer space like square or so."*
N07	*"Firstly, I would try to get away probably to wide and open space."*
N09	*"I think open space, or place where things are not so crowded, so I think I would be looking for an open space."*
N11	*"You want to run away to safety, somewhere where other people go, more open area."*
N13	*"If there were people trying to get away, I might try to say, I know where I was going, I know the area, come with me and try to get to some open space; perhaps the market square, or somewhere near the castle, or somewhere where you have got more open space."*
L05	*"Just to get away from that scene somewhere to an open space."*
L11	*"Head away, obviously, find yourself quiet side street and just head as far away from it as you can towards some open area."*
	Incident area
P03	*"If I would see somebody in desperate need of help, yes I would stay in the area. I think it will be an immediate reaction if you see somebody in distress, you want to help them. I think if the person was able to move away, to get the person to move. But if the person wasn't able to move, then I would sit with them and talk to them until a professional help arrive."*
N08	*"I feel like I would actually stay where I was, because ... help is going to come, I just don't think it would be a good thing to move too far away. I would try to stay in the area."*
N12	*"My instinct is to trust emergency services and to think to be close to them that would mean to be safe. Maybe the best thing to do is to just stay where I am and wait for somebody to tell me."*
L06	*"A curiosity, I think I might have a look. I would watch the emergency services."*

Table 6.4: Categories of preferred destinations.

The textual information is quantified in a contingency table (Table 6.5) which serves as background information for the normalisation process (Table 6.6) and creation of the stacked bar charts (Figure 6.2).

Participant	Home	Open space	Incident area
P3			1
P4		1	
N01	1		
N02	1		
N03		1	
N05	1		
N06		1	
N07		1	
N08			1
N09		1	
N10	1		
N11		1	
N12			1
N13		1	
L02	1		
L03	1		
L04	1		
L05		1	
L06			1
L07	1		
L08	1		
L09	1		
L10	1		
L11		1	
Total	11	9	4

Table 6.5: Demographic characteristics of the total sample and its distribution with respect to preferred destinations.

Category	Home	Open space	Incident area
Total [%]	46	38	16
Nottingham [%]	29	50	21
Leicester [%]	70	20	10
Nottingham norm [%]	13	27	11
Leicester norm [%]	33	11	5
female [%]	46	38	16
male [%]	45	36	19
female norm [%]	23	20	8
male norm [%]	23	18	8
$<$ 40 years [%]	53	40	7
$\geq$ 40 years [%]	34	33	33
$<$ 40 years norm [%]	28	21	3
$\geq$ 40 years norm [%]	18	17	13

Table 6.6: Distribution of preferred destinations with respect to demographic categories and results of data normalisation applied to SSI dataset.

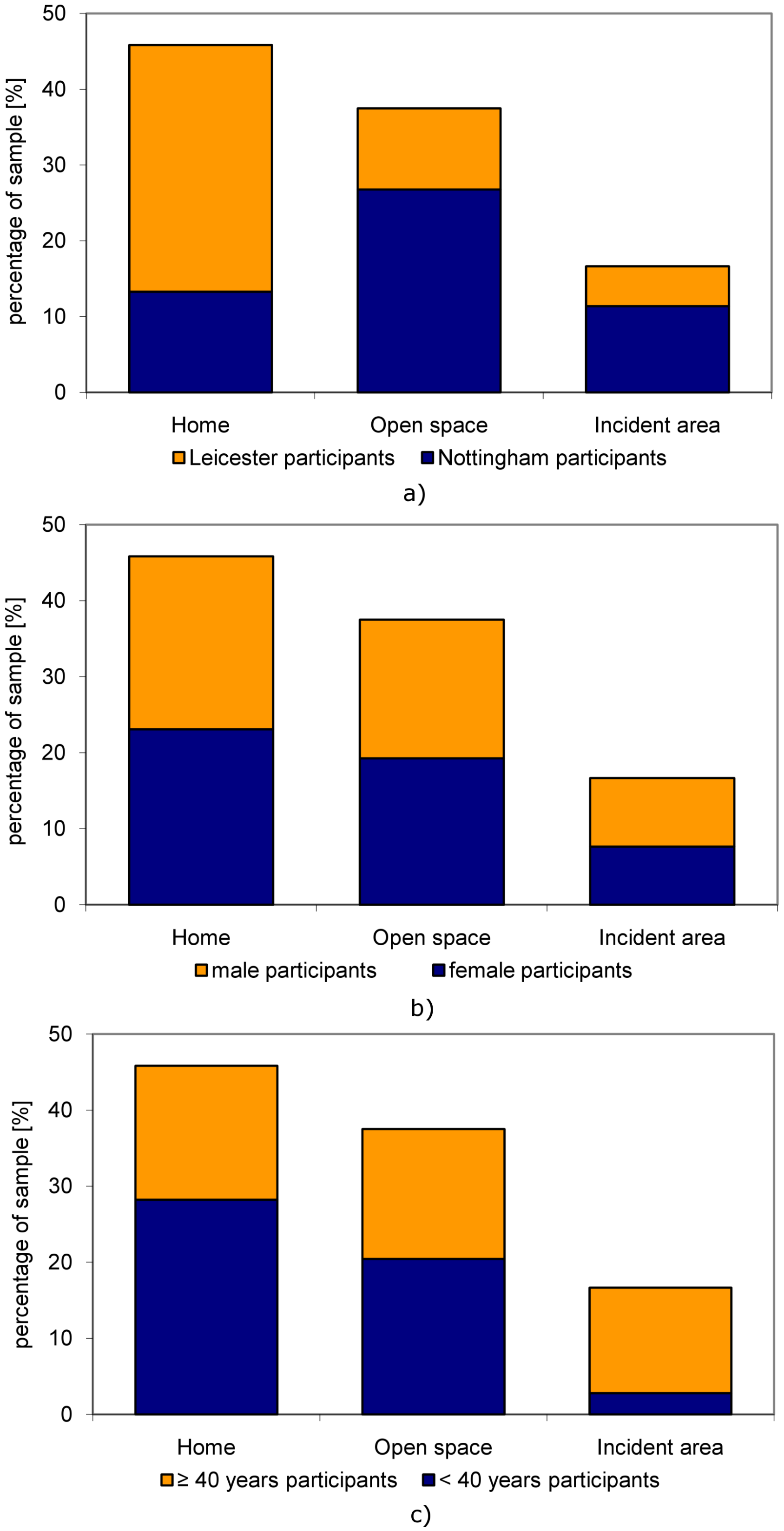

Figure 6.2: Distribution of preferred destinations with respect to different demographic categories.

The stacked bar charts in Figure 6.2 show that although approximately 1/3 of the participants would provide assistance to other people, only a small proportion would actually remain in the *Incident area* (16 %). This suggests that the assistance would be directed towards people with minor injuries (mobile casualties) or those who are not familiar with the area and need to be directed towards safer places. The small number also reflects the fact that people are aware of the danger they would have to face if they decided to stay. Almost half of the population sample (46 %) specified that their primary intention would be to get *Home*. *Open space* located near the incident area was selected by 38 % of the participants as the most preferable destination.

The difference in the priorities are most apparent with respect to the location of the participants. A larger proportion of *Nottingham* participants would remain in the *Incident area* or proceed towards the nearby *Open spaces*. This corresponds with the predominant assistance-oriented behaviour of people from Nottingham as identified in the previous section. After the initial shock subsides, the majority of the *Leicester* participants (70 %) would adopt evacuation behaviour towards their *Homes*. From the participants that would remain in the *Incident area* the majority were representants of the $\geq$ *40 years of age* group. The distribution with respect to the gender of the participants is almost equal.

6.5.3 Aim 3: Factors

CA of both datasets was conducted to extract factors that have an influence on human decisions in the CBRN emergency situations. The results of the analysis are reported separately for SSI and PEI datasets to enable subsequent comparison.

6.5.3.1 Analysis of SSI Dataset

The factors specified in the SSI study are organised into Table 6.8 together with a description of the effects they have on the response behaviour. The information used for defining the factors is presented in Appendix H.

Participant	Road width	People	Traffic	Familiar route	Local amenities	Secondary explosion	Shortest and fastest route	Emergency services	Transportation accessibility	Total
P3		1	1	1	1			1		5
P4	1			1					1	3
N01	1	1	1			1				4
N02	1	1	1			1				4
N03	1	1				1	1	1		5
N05	1	1	1		1	1	1		1	7
N06	1		1				1			3
N07							1		1	2
N08		1			1					2
N09	1	1	1							3
N10	1	1	1	1	1					5
N11	1	1		1				1		4
N12						1		1		2
N13	1	1	1	1	1	1		1		7
L02	1	1	1	1						4
L03					1		1			2
L04	1			1						2
L05	1	1		1						3
L06								1		1
L07		1			1		1			3
L08	1	1	1				1			4
L09	1	1								2
L10	1	1	1			1				4
L11	1	1								2
Total	17	17	11	8	7	7	7	6	3	

Table 6.7: Distribution of the total sample with respect to factor categories extracted from SSI dataset.

The contingency table (Table 6.7) depicts the distribution of the factors among the population sample. The last row indicates the frequency with which the factors were referenced and the last column sums the number of factors dis-

Factor	Description	Effects
Road Width	feeling of openness the participant has when staying on the street	the preference of the population sample can be divided into three categories based on perception of safety: (i) wider and more open roads, (ii) narrow and more enclosed roads, (iii) roads not too wide nor too narrow
People	number of people visible on the street, or people that can emerge from surrounding buildings or streets	the influence can be organised into two categories: (i) avoid crowds at all costs (ii) affiliate with a reasonable number of people
Traffic	number of driving or stationary vehicles or parked cars	try to avoid busy areas with fast driving or congested traffic
Familiar Route	walking in familiar areas	the intention to proceed towards the preferred destination on a route which is sufficiently familiar to the evacuee
Local Amenities	shops, banks, market stalls and other services along the street; often associated with a stream of people emerging onto the street	try to avoid retail areas since they might be targeted for a secondary explosion or due to the large number of people which might emerge onto streets
Secondary Explosion	additional blasts	avoid areas that might be targeted for a secondary explosion (office buildings, shops, crowded pedestrianised zones, etc.)
Shortest or Fastest Path	the most direct or fastest route	the intention of following a route which seems the shortest or fastest towards the target destination
Emergency Services	presence of personnel from any emergency service organisation (e.g. police, fire and rescue service, etc.)	prospects of help, advice and support
Transportation Means	availability of public or personal transport: bus, train, tram, taxi or own car	the preference is organised into two categories based on a feeling of safety (i) avoid public transportation and bus or train stations due to the danger of a secondary explosion (ii) prospect of faster evacuation from the area

Table 6.8: Factors identified by content analysis of SSI dataset.

Category	Road width	People	Traffic	Familiar route	Local amenities	Secondary explosion	Shortest and fastest route	Emergency service	Transportation accessibility
Total [%]	71	71	46	33	29	29	29	25	13
Nottingham [%]	71	71	57	36	36	43	29	36	21
Leicester [%]	70	70	30	30	20	10	30	10	0
Nottingham norm [%]	36	36	30	18	19	23	14	20	13
Leicester norm [%]	35	35	16	15	10	6	15	5	0
female [%]	69	85	46	38	31	31	23	31	8
male [%]	73	55	45	27	27	27	36	18	18
female norm [%]	35	43	23	20	15	15	11	16	4
male norm [%]	36	28	23	13	14	14	18	9	9
$<$ 40 years [%]	80	73	33	27	13	40	33	20	20
$\geq$ 40 years [%]	56	67	67	44	56	11	22	33	0
$<$ 40 years norm [%]	42	37	15	13	6	23	17	9	13
$\geq$ 40 years norm [%]	29	34	31	20	23	6	12	16	0

Table 6.9: Distribution of factors with respect to demographic categories and results of data normalisation applied to SSI dataset.

cussed by an individual participant. The frequencies are normalised in Table 6.9 and the distribution of the population sample among the factors after the data normalisation is illustrated in the three stacked bar charts in Figure 6.3. The stacked bar charts in Figure 6.3 show that the two most frequently referenced factors (71 % of the participants) are the *Road width* and the number of *People* present on the street. The fear of *Traffic* is categorised as the third (46 % of the population sample). The remaining factors were referenced by 25 % - 33 % of interviewees with the following exception. Possibly due to the close proximity of *Home* from the city centre, participants did not express the need for transportation. This might be a reason of the lower interest in the *Transportation accessibility* factor (13 %). However, since addresses of the participants were not collected, such assumption cannot, with the information in hand, be verified.

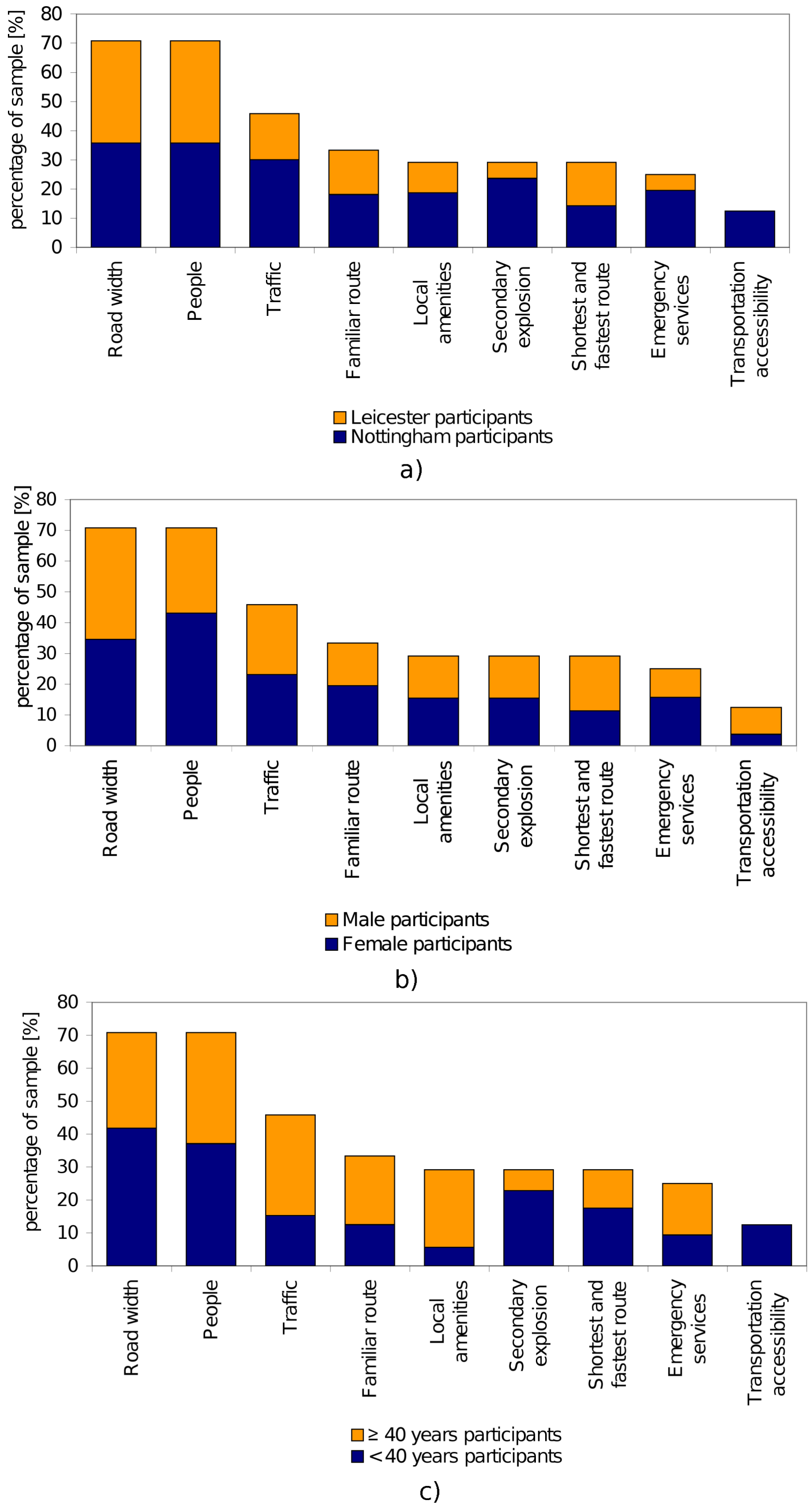

Figure 6.3: Distribution of factors extracted from SSI dataset with respect to different demographic categories.

With respect to the demographic categories (Figure 6.3) the three most prominent factors are almost equally distributed signifying that their preference is independent of the demographic background. The remaining factors are more or less independent of the gender of participants. However, some differences can be observed regarding the location of the participants (image a)). They are related to:

- *Transportation accessibility*; reflecting that participants from Nottingham possibly live outside the central area, hence requiring transportation to get home.
- *Secondary explosion*; higher concern of Nottingham residents possibly due to the high crime rates labelling Nottingham as the "crime capital" of England and Wales (BBC NEWS, 2006).
- *Emergency services*; interest in looking for help and advice is higher in Nottingham possibly due to the higher crime awareness.

Figure 6.3 c) indicates that no apparent differences in distribution can be observed with respect to the gender of the participants. Several differences are visible in image c) depicting the distribution of the factors among the two age categories. While *Traffic, Familiar route, Local amenities* and *Emergency services* were of concern for the older population sample, *Secondary explosion* and *Transportation accessibility* were more often referenced by the younger category. This finding might indicate that population over forty years of age feel safer in familiar areas that are not busy with people and traffic. Since younger people would be more concerned about additional explosions they would try to avoid vulnerable areas such as train or bus stations and public transportation which were targeted in historical terrorist attacks (e.g. 7/7 London bombings).

6.5.3.2 Analysis of PEI Dataset

The factors identified by CA of PEI dataset are described in Table 6.12. Appendix I contains references to the photographs based on which the factors were defined. The same factor was often discussed several times from different perspectives regarding more than just one photograph. Even though the factors were defined with consideration of all the recorded comments, to keep the transcript transparent only one reference per participant is included for demonstration purposes.

The contingency table (Table 6.10) depicts the distribution of the factors among the participants. The information is normalised in Table 6.11 and graphically displayed as stacked bar charts in Figure 6.4. The *Road width* is the most frequently referenced factor (88 % of the population sample; Figure 6.4). The following two factors equally proportioned among the participants are *Moving traffic* and *People* (63 %). The frequency of the remaining factors vary between 46 % (*Personal feeling*, *Physical obstacles*) and 21 % (*Local amenities*, *One way traffic*, *Secondary explosion*, *Transportation means*).

The distribution of the factors with respect to the origin of the participants is almost equal with an average difference of 7 % (Figure 6.4 a)). The first three most frequently referenced factors in image b) are independent of the gender of the participant. However, the importance of the remaining factors (with exception of *Local knowledge* and *Secondary explosion*) inclines more towards the *male participants*. An exception in this trend can be observed in the distribution of the *Local knowledge* factor which was predominantly referenced by female participants (69 %). This may imply that women feel more comfortable by following familiar roads and avoiding areas which are known as not safe (e.g. dark narrow alleys, subways, etc.).

Participant	Road width	Moving traffic	People	Personal feeling	Physical obstacles	Local knowledge	Buildings	Exit routes availability	Road type	Pavements	Road crossing difficulty	Visibility	Local amenities	One way traffic	Secondary explosion	Transportation means	Total
P3	1	1			1	1					1		1	1			7
P4	1						1	1						1		1	5
N01	1	1	1			1	1								1		6
N02	1	1	1		1	1		1									6
N03	1	1	1	1			1		1	1	1					1	9
N05	1	1	1	1			1		1				1		1	1	9
N06	1	1	1		1				1	1			1	1			8
N07	1																1
N08	1					1		1									3
N09	1	1	1	1		1						1					6
N10	1			1	1		1	1	1	1	1	1					9
N11	1	1	1	1	1			1		1							7
N12	1	1		1	1			1	1	1	1	1		1			10
N13	1	1		1	1	1	1		1						1		8
L02	1		1		1	1			1								5
L03			1		1							1					3
L04						1										1	2
L05	1	1	1	1			1	1									6
L06	1				1	1					1						4
L07			1			1											2
L08	1	1	1	1	1		1		1	1		1					9
L09	1	1	1								1		1	1	1		7
L10	1	1	1	1			1	1					1		1	1	9
L11	1	1	1	1						1		1					6
Total	21	15	15	11	11	10	9	8	8	7	6	6	5	5	5	5	

Table 6.10: Distribution of the total sample with respect to factor categories extracted from PEI dataset.

Category	Road width	Moving traffic	People	Personal feeling	Physical obstacles	Local knowledge	Buildings	Exit routes availability	Road type	Pavements	Road crossing difficulty	Visibility	Local amenities	One way traffic	Secondary explosion	Transportation means
Total [%]	88	63	63	46	46	42	38	33	33	29	25	25	21	21	21	21
Nottingham [%]	100	71	50	50	50	43	43	43	43	36	29	21	21	29	21	21
Leicester [%]	70	50	80	40	40	40	30	20	20	20	20	30	20	10	20	20
Nottingham norm [%]	52	37	24	26	26	22	22	23	23	19	15	10	11	16	11	11
Leicester norm [%]	36	26	39	20	20	20	16	10	10	10	10	15	10	5	10	10
female [%]	85	62	62	31	38	69	23	23	23	15	23	8	15	15	23	15
male [%]	91	64	64	64	55	9	55	45	45	45	27	45	27	27	18	27
female norm [%]	43	31	31	15	19	37	11	11	11	7	11	4	8	8	12	8
male norm [%]	45	32	32	31	27	5	27	22	22	22	14	21	13	13	9	13
$<$ 40 years [%]	87	73	73	53	27	27	47	40	27	33	20	20	20	20	27	33
$\geq$ 40 years [%]	89	44	44	33	78	67	22	22	44	22	33	33	22	22	11	0
$<$ 40 years norm [%]	44	39	39	28	12	12	26	21	12	18	9	9	10	10	15	21
$\geq$ 40 years norm [%]	44	24	24	18	34	30	12	12	21	11	16	16	11	11	6	0

Table 6.11: Distribution of factors with respect to demographic categories and results of data normalisation applied to PEI dataset.

Table 6.12: Factors identified by content analysis of PEI dataset.

Factor	Description	Effects
Road width	the distance from one side of the street to the other including pavements or any other walk-on areas such as traffic islands or green zones between roads	same as defined in the SSI categories
Moving traffic	number of vehicles driving on the road	same as defined in the SSI categories
People	number of people visible on the street	avoid large crowds of people mostly connected with pedestrianised areas
Personal feelings	subjective view of the situation regarding safety of the person on the particular road; usually influenced by openness of the area, perception of the street orientation towards the outskirts of the city, and to a degree associated also with combination of other listed factors	can be of positive (attraction to the area) or negative (repulsion) nature
Physical obstacles	all objects that can in any way obstruct pedestrians in free movement; for example parked cars, benches, trees, bus stops, railings, etc.	necessity to avoid places with physical obstacles
Local knowledge	level of familiarity with the area	can be in nature positive (attraction to the area) or negative (repulsion)
Buildings	the number of floors and height of buildings on either side of the street	can be of positive (protection) or negative (additional danger from collapsing or secondary explosion) nature
Exit route availability	possibility of changing to another street; often connected with visibility of junctions on the selected street	try to avoid areas that have no visible exits in case of sudden changes in the situation (long funnels)
Road type	characteristics of the road associated often with amount of moving traffic, width and use of the road	participants have reported four considered road types: main road, side road, dual-carriageway and pedestrianised area; all four road types have negative or positive effect depending on preferences of the participant
Pavements	availability, quality and width of pavement	preference of streets with wide pavements on both sides of the road

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Factor	Description	Effects
Road crossing difficulty	availability of pedestrian crossings, traffic lights or other places suitable for road crossing; often connected with amount of moving traffic, barriers or railings	avoid roads that are difficult to cross
Visibility	a measure of distance at which people can clearly see into the street in front of them; often associated with the street straightness and number of obstacles blocking the view e.g. people or stationary objects like trees, bus stops, etc.	good visibility makes the street more attractive
Local amenities	shops, banks, market stalls and other services providing facilities on the street; often associated with additional people coming to the street	same as defined in the SSI categories
One way traffic	associated with traffic coming only from one direction	have positive effect on the decision since the movement of the vehicles can be more easily observed
Secondary explosion	threat of additional blasts	same as defined in the SSI categories
Transportation means	availability of public or personal transport: bus, train, tram, taxi or own car	same as defined in the SSI categories

With respect to the different age categories the population above 40 years of age would rely more on *Local knowledge*. In addition, the concerns regarding *Physical obstacles* were also referenced more frequently by the older age category. The most significant difference can be observed with respect to *Transportation means* where this factor was not mentioned by any participant over 40 years of age.

6.5.4 Aim 4: Comparison of SSI and PEI Findings

The only conceptually similar data that were collected by both experiments are related to the factors that are considered during selection of the route towards the preferred destination. The two techniques and their outputs are compared by qualitatively assessing similarities and differences between the definition of the identified factors.

In total participants in PEI reported 16 different factors which is almost double the number of factors identified by SSI (9 factors). The larger number of factors reported in the PEI might be a consequence of:

- finer representation of concepts which are in SSI depicted by a single and more general factor; for example PEI factors *Road width, Personal feelings, Physical obstacles, Buildings and Visibility* are in SSI generalised into a *Road width* factor representing the openness of the street;
- presentation of new concepts not considered in SSI; for example *Road crossing difficulty, Pavements*.

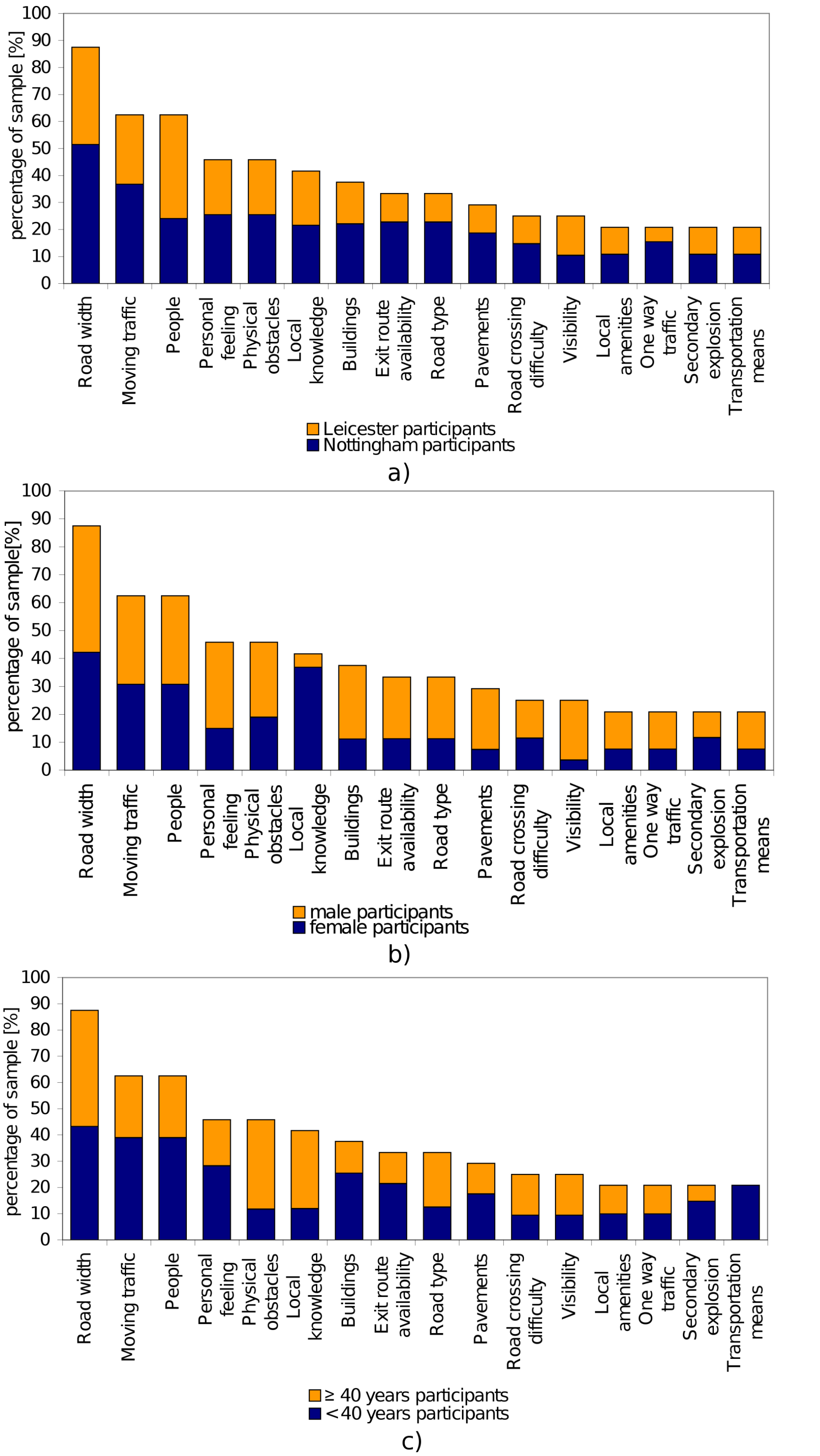

Figure 6.4: Distribution of factors extracted from PEI dataset with respect to different demographic categories.

These findings support the argument of Harrison (2002) and Harper (2002) who specify that due to the visual representation of the studied phenomenon, PEI can trigger additional and more specific considerations than interviews.

The definitions of the similar factors do not conceptually differ. In addition, the first three most frequently referenced factors in both datasets were found to be the same. These are related to the characteristics of the environment and the dynamics of the situation represented by the movement of people and vehicles. This suggests that both experimental studies lead to the same findings. However, these similarities might be a consequence of the adopted information extraction approach (CA). In CA the definition of the content categories and the classification of the findings is biased by the opinion of the researcher. In order to eliminate existing bias the next step would be to present the transcripts of both experiments separately to independent analysts. The outcomes of the analysis can then be compared to identify whether the same information was extracted. Alternatively, based on the identified categories, more focussed qualitative data collection experiments can be defined to enable formal statistical assessments.

6.5.5 Aim 5: Generalisation of the Findings

Data saturation was conducted to identify whether the size of the population sample was appropriate. The data saturation has been applied to assess information collected with respect to the:

- response behaviours (Figure 6.5 a));
- preferred destinations (Figure 6.5 b));
- factors reported in SSI and PEI datasets (Figure 6.5 c) and d))

The aim of the analysis was to identify how new information emerged during the interviewing process. The order of the participants in the graphs corre-

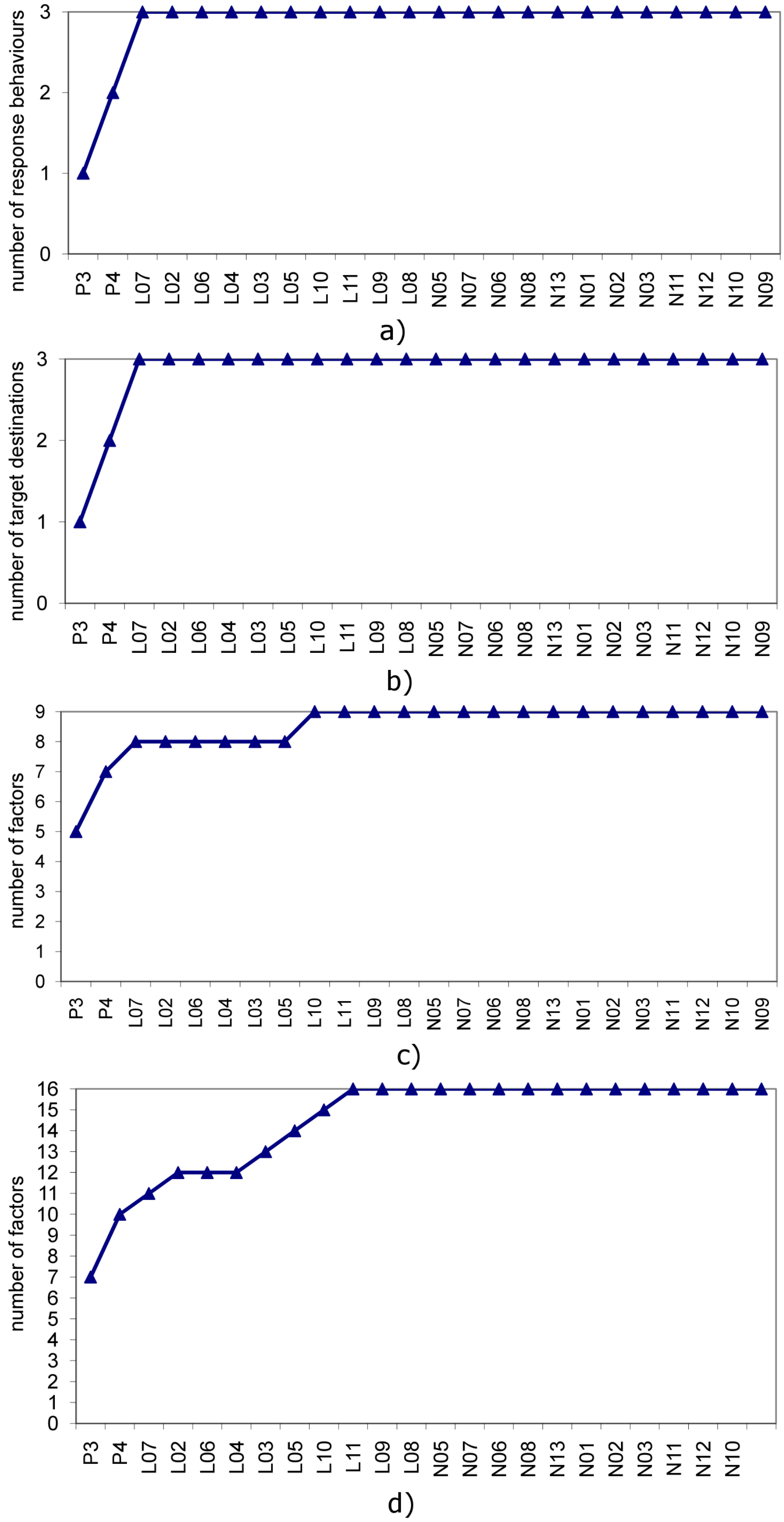

Figure 6.5: Data saturation.

sponds to the order in which the interviews were conducted. The visual inspection of the progress of the cumulative function indicates how new information was added to the findings by further interviews.

Figures 6.5 a) and b) indicate that no new response behaviour and preferred destination, respectively, were reported after the first three interviews. The final number of factors for both experimental studies (SSI and PEI) was reached after the ninth and tenth interview (Figure 6.5 c) and d)).

The analysis indicates that in all cases data saturation was reached before even half of the selected population sample was interviewed. This may suggest that the findings of the reported analysis can be generalised to the whole population. As was reported in the previous chapter the selection of the population sample was not conducted randomly. Hence, the findings cannot be adopted as representative of the whole population. However, the results of the saturation indicate that the size of the interviewed population is adequate to gain a general understanding of the response behaviour since no new information was gained after 10th interview.

6.6 Summary

The aim of this chapter was to present an approach to analysis of the data collected by the empirical studies presented in Chapter 5. Due to the qualitative nature of the data, the focus was put on extracting primary information that characterises the behaviour of people in CBRN emergency situations. The collected information was organised into contingency tables and was subsequently normalised and graphically displayed to obtain additional quantitative insight. The findings of this analysis cannot be generalised to the whole population. Nevertheless, they have provided information based on which the InSiM conceptual model can be defined in Chapter 7 to demonstrate how development of a geo-simulation model can benefit from empirically collected data.

The main findings of the analysis are:

- The most common response reactions to a CBRN explosion are:
  - assistance to injured and distress people;
  - evacuation from the incident area;
  - shock due to the sudden unexpected event.
- Once aware of the incident people would move to the following destinations:
  - home;
  - open space situated in the proximity of the incident;
  - the incident area.
- The three most frequently referenced factors influencing human decisions on which route to follow are:
  - SSI: road width (71 %), people (71 %), and traffic (46 %);
  - PEI: road width (88 %), moving traffic (63 %), and people (63 %).

The analysis also identified several trends characterising preferences of people with a specific demographic background. These trends are:

- The form of the response behaviour is influenced by the geographic location of the participants. The Nottingham population sample inclined towards assistance while the Leicester participants reported that they would be in shock.
- The location of the participants affects the selection of the preferred destination towards which the interviewees would navigate. Nottingham participants reported the open space area and the location of the incident as the destinations of preference while the preference of the Leicester participants was to move towards home.

- The selection of the preferred destination is also influenced by the age of the participant. The area of the incident was reported as the destination of preference by people over forty years of age.

- The three most frequently referenced factors that influence human decision in CBRN emergency situations are independent of the demographic characteristics of the participants.

Additional investigation in the form of more focussed qualitative or quantitative research is necessary to gain further understanding of the origin of these trends.

Chapter 7

Development of InSiM Conceptual Model

7.1 Introduction

This chapter discusses the development of a conceptual model which represents the key processes and essential characteristics that are implemented in InSiM (Chapter 8). Carley (1996) argues, that the aim of the conceptualisation process is to determine the level of simplification of the real-life concepts to fulfill the needs of the geo-simulation model and at the same time realistically represent the real situation. This is done by specifying and justifying a set of concepts indicating the model scope and limitations.

The conceptual model draws upon findings from the analysis of the experimental data presented in the previous chapter. The conceptualisation process is discussed with respect to the set of aspects identified in the literature review (Section 2.3.1) as the key considerations for development of a geo-simulation model for the purpose of disaster management. The specific aspects of this development step are:

- *Human Behaviour Representation & Parameterisation*,
- *Environment Representation & Sense of Space and Place*,

- *Reasoning Process*.

These aspects are organised into three key elements (building blocks) that form the conceptual model:

- **the simulation space** (Section 7.2): depicts the characteristics and representation of the synthetic space within which the agents interact;
- **agent specification** (Section 7.3): definition of the main agent characteristics, behaviours, and interactions;
- **general model characteristics** (Section 7.4): definition of key model components, as well as attributes and processes related to operation of the model.

The remainder of this chapter describes the conceptualisation process that underpins the definition of these elements for InSiM.

7.2 Simulation Space

To simulate the response to a CBRN incident in real-life environments, the simulation space of InSiM needs to incorporate data representing a real geographic area. According to the Home Office (2004) the most vulnerable locations to potential CBRN terrorist attack are:

- critical or iconic locations (e.g. governmental buildings, historical monuments or other POI)
- high profile events (e.g. sport tournaments, political campaigns, concerts, visit of a VIP etc.)
- other areas with high concentrations of people (city centres, parks, etc.).

The *city centre* area was selected as the location of the CBRN explosion simulated by InSiM. The key reasons are as follows:

- City centres are areas which are for the most of the day populated by a large number of people.
- It is possible to test a similar scenario on more than one (and very specific) location or one unique event (e.g. 2012 Olympic games in London).
- The experimental studies focused on capturing human reaction in open spaces and not enclosed areas such as stadiums, railway stations or tube stations. Hence, the simulation environment needs to correspond with the areas for which the data were collected.
- City centres are areas of high concentration of shops and local businesses where an explosion would have the maximum effect in disturbing the course of everyday life of a significant number of people.

7.2.1 The Incident

According to Hampson (1988) city centres are connected with local retail facilities. Therefore, the city centre is often seen as a synonym to the "high street" or centrally located shopping centre (Le, 2007). Hence the most "appropriate" location for the CBRN bomb in InSiM would be an entrance to a large shopping centre which is, during working hours, constantly busy with a large number of shoppers.

The explosion represented in InSiM corresponds to a bomb in a backpack as was the case of 7/7 London bombings in 2005 (BBC News, 2005). The threshold of severe wounds caused by the direct blast and flying debris of a backpack-size explosion is approximately 45 m (FEMA, 2003, pg. 4-8). Based on discussion with two Nottinghamshire experienced incident commanders the incident awareness radius was selected to be 120 m for a city centre area (Jones and Whelan, 2007).

7.2.2 Generalisation of the Complex Geographical Space

The analysis of the experimental data (Section 6.5.2) revealed that the key part of human response to an emergency is expressed by movement towards a specific preferred destination. Movement is connected with the navigation of a person from one place to another. Therefore, the simulation environment in InSiM needs to be represented in a way which can effectively incorporate the navigational demands of agents.

In addition, it was identified that people would not search for shelter in surrounding buildings. Although building height was identified as one of the factors that influence human decision in emergency, it was referenced by only 38 % of the participants. Based on these findings it was decided to exclude buildings in the representation of the geographical space and concentrate on factors of more importance (i.e. more frequently referenced ones).

The central retail areas (in large British cities) are usually heavily built-up. Hence they often lack larger green spaces or parks since they are usually located in the old historical centre of the city. Therefore, the majority of the outside space consists of paved local street, roads or pedestrianised zones. Due to a lack of other "walkable" areas, it was decided to further generalise the environment to roads only.

7.2.3 Representation of the Simulation Environment

The simulation environment can be represented in several different ways (raster, geographic network, social network, continuous space, cyberspace; Section 2.3.2.3). Cyberspace representation was found unsuitable for InSiM since its characteristics in principle differ from the context of this research. Continuous space was found inappropriate since the focus is put on observing global patterns rather than low-level behaviours. Hence, the level of detail captured in the continuous space would be unnecessarily complex.

Due to the format of the geographic data from which the environment is generated (see the following section) cellular space representation would be impractical because it would require additional pre-processing which would result in information loss. In principle, the aim of InSiM is to simulate the dispersion of people which could be also viewed as a flow. In GIS, flows of goods or services are commonly represented by network data models, since its structure is specifically developed to capture connectivity between individual network segments (Longley et al., 2002, pg. 192). Hence, it was decided that the most feasible representation for the InSiM environment would be a *geographic network model*.

7.2.4 Use of Real Geographic Data for the Definition of the Road Network

The OS MasterMap database (OSMM; Ordnance Survey, 2009) was used as the source of the geographic data. Since OSMM contains high resolution data covering the whole of Great Britain, its incorporation into InSiM provides flexibility for application of the model on different cities across the country. OSMM consists of several layers, two of which contain relevant data:

- Topographic
- Integrated Transport Network (ITN).

While the Topographic layer represents all real-word features (roads, buildings, rivers, structures, administrative boundaries, etc.) the ITN layer only includes the representation of roads. The Topographic layer is depicted in a vector format (points, lines, and polygons) while the ITN layer consists of a fully topologically structured network (Ordinance Survey, 2006). Due to its network structure the ITN layer was selected as the base geographic database for the generation of the simulation environment.

The geometry of a road in the ITN layer is organised into two datasets:

- **RoadLink**: depicts the general alignment of a road section. RoadLinks are broken at: (i) intersections, (ii) the end of roads, (iii) where the attribution of the road changes, or (iv) where there is a change of name. RoadLinks are represented as polylines.
- **RoadNode**: is coincident with the end of all RoadLink features. RoadNode is represented as a point geometry (Ordnance Survey, 2009).

It was suggested in the meeting with the Nottinghamshire incident commanders that the behaviour of people should be captured for two time intervals: 15 minutes and 30 minutes after the blast (Jones and Whelan, 2007). Since the average speed of a pedestrian is approximately 3 km/h (Dewar, 1992) the average person could, in a 30 minute period, walk approximately 1.5 km. Therefore, the extent of the simulation environment was selected to cover area of approximately 3 km x 3 km with the incident located near the centre of the rectangle.

7.2.5 Processing Real Geographical Data

Two datasets containing ITN layer data, representing Nottingham and Leicester city centres, were downloaded from the Digimap web service (EDINA, 2009). The downloaded data corresponded to the extent of the defined use case scenarios (see Section 8.3). However, due to the complexity of the road network and the large number of attributes associated with every feature in the ITN layer, the datasets needed to be further generalised. The adopted process was as follows:

1. **Removing redundant polylines**: In this step the multi-line features such as *Traffic Island* and *Dual Carriageway* (Figure 7.1 a)) from the RoadLink original dataset were collapsed into a single line (data processed by Thorm (2008) from Ordnance Survey by request; Figure 7.1 b)).

2. **Removing redundant points**: The polylines representing each RoadLink feature were further simplified by removing redundant points and straightening the road network edges (use of *Simplify Line* function of the Data Management Toolbox of ArcInfo 9.2; the tolerance for the POINT_REMOVE algorithm which characterises the maximum allowable offset was set to 10 m; Figure 7.1 c)). The new length of each RoadLink feature was compared with its length before the simplification process. The maximum difference was 50 cm for the Nottingham dataset and 30 cm for the Leicester dataset respectively. Therefore, it could be concluded that elimination of nodes in the polyline did not significantly alter the polyline length.

3. **Creation of the road network**: The polylines were decomposed into individual line segments to create the nodes and edges of the road network graph (use of *Split a polyline at the vertices* ArcObject code (ESRI Support Centre, 2009)).

4. **Assigning attributes**: Each of the newly created line segments was assigned an attribute value to reflect its characteristics (Figure 7.1 c)). This step is further discussed in the following section.

Table 7.1 provides information regarding the number of RoadLink features after each generalisation step. It can be observed that if the second step (removing redundant points) was not applied the number of the road network edges would be almost triple. This would significantly slow down the simulation speed (comparison of *graph edges* and *final graph edges*).

The final road network forming the simulation space is represented as a bi-directional geo-referenced graph. Bi-directional means that agents can move in both directions over the simulation space. Each node of the graph is geo-referenced, i.e. eastings and northings in the Ordnance Survey National Grid are known for each node of the graph.

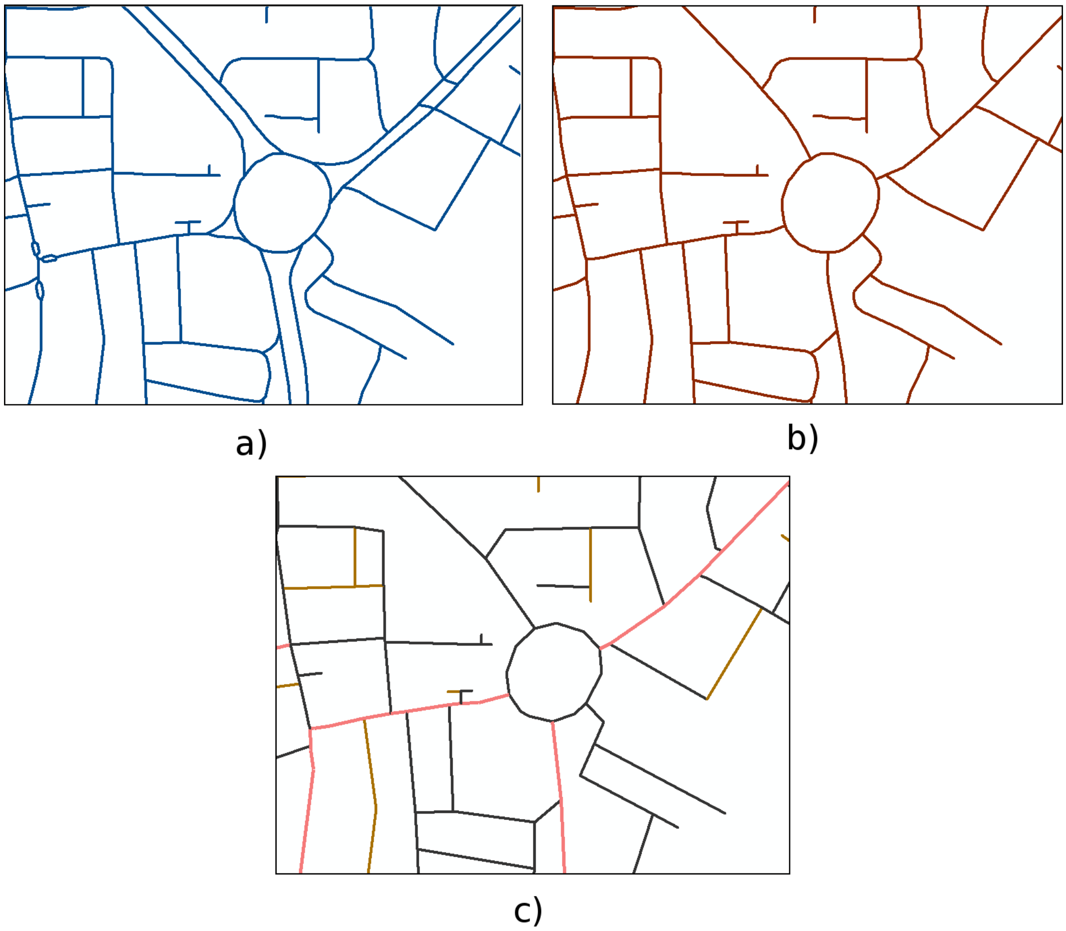

Figure 7.1: Creating the simulation environment.

Generalisation step	Data type	RoadLink features Nottingham	RoadLink features Leicester
Original ITN	RoadLink	2763	3083
OS generalised data	RoadLink	2672	2954
	graph edges	7848	7328
Polyline simplification	RoadLink	2672	2954
	final graph edges	2979	3287

Table 7.1: Number of RoadLink features during generalisation of the ITN layer.

7.2.6 Attributes of the Road Network

The width of the road has been identified as the most frequently referenced factor that influences human decision making during emergency situations (see Section 6.5). This factor was discussed by 71 % of participants in the SSI studies and by 88 % of participants in the PEI studies respectively. To demonstrate the importance of real-life information in ABM for disaster management, this factor was selected as the characteristic by which the road network is described. Additional factors can be incorporated once InSiM is fully functional.

The road width does not necessarily only represent the width of the actual carriageway. In comparison to cars (which can only drive on designated areas) pedestrians are more flexible and can also walk in areas with restricted vehicular access. Therefore, the road width is, in this instance, also associated with pavements, green areas (e.g. strip of grass between two carriageways), or any other open spaces within which people can freely navigate. This factor is subsequently referenced to as *walkway width* to highlight the difference. An example of a walkway width is provided in Figure 7.2, where the walkway is defined as a composite of two carriageways (c_1, c_2), pavements on both sides and between the carriageways (p_1, p_2, p_3), green areas around the pavements (g_1, g_2) and other surfaces (o).

7.2.6.1 Forming Walkway Width Categories

To identify walkway width categories an additional review of the PEI transcripts is needed. The focus is put on responses referencing walkway width on a specific photograph. The transcripts that are used for identification of the walkway width categories are provided in Table 7.2.

Since the exact location of each photograph is known (see maps in Appendices E and F), it is possible to measure the approximate width of the walkway in that

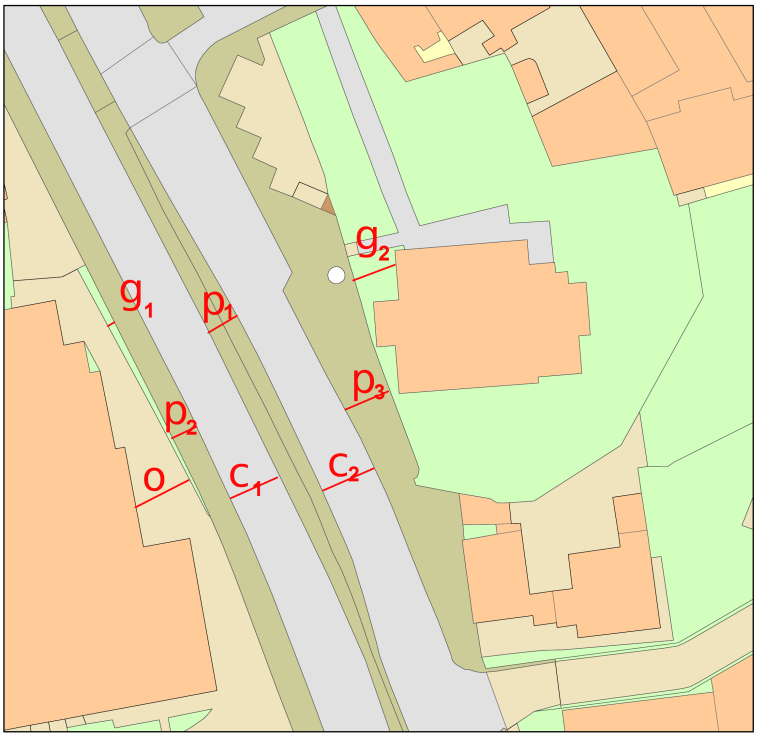

Figure 7.2: Definition of walkway width.

particular place (use of the *Measure* tool in ArcMap). Table 7.3 contains street name and the walkway width (rounded to the nearest meter) of the area captured in the photographs. It also organises the information into an initial set of walkway width categories with the frequencies of how many times they were referenced.

The distribution of these initial categories around the width scale is depicted in Figure 7.3. The concept of width is subjective and perceived differently by different participants. This is demonstrated by fuzzy boundaries between the four categories.

During the PEI dual carriageways have been identified as wide and open streets. However, they were placed on the lower preference positions due to the busy traffic (see Appendix J where 1 determines the photograph of highest preference and 6 of the lowest). As Table 7.3 indicates, 57 % of the *Wide all* category is formed by dual carriageways.

Participant	Photograph	Comment
P3	6L 2L 5L	*"... looks quite wide."* *"... seems like quite an open space."* *"... quite a narrow street, back street."*
P4	2L 33N 22N 5N	*"... it is an open space and a big road."* *"... quite a wide area."* *"The width of the road is good."* *"... looks like a long narrow corridor."*
L02	5L	*"... little side street and quite dark."*
L06	5L 6L	*"... it's quite narrow."* *"... fairly wide ..."*
L04	16N	*"... streets are closer together."*
L05	1N	*"... nice and wide."*
L10	1N 28N 5L 2N	*"... it's quite wide."* *"... quite wide ..."* *"It looks a bit closed off."* *"... quite a narrow street."*
L11	4L 5N	*"... it is narrowing down."* *"It's narrow."*
L09	5L	*"... it is not actually that narrow."*
L08	6L 16N 5L 3L 12L	*"... it is fairly wide and fairly open."* *"... it's a narrow road, it's more closed in ..."* *"... much narrower street, there is not much space."* *"It's a wide road."* *"It's a wide open road."*
N07		The photos were ordered purely based on their width from the widest (most preferable) to the narrow ones.
N06	10N 17N	*"It is a relatively wide road."* *"This one is very narrowish."*
N08	22N 9L 13L	*"... quite a big and open space."* *"It's quite an open space."* *"It looks wide and spacious."*
N01	10N 22N 16N	*"... this one is quite wide."* *"... nice wide road..."* *"... not quite as wide."*
N02	10N	*"It is a wide street."*
N03	16N 10N 33N 5N	*"It is a relatively small street."* *"... fairly narrow street."* *"... it is a bit wider."* *"It's quite narrow."*

Table 7.2: References to walkway width extracted from the PEI dataset.

Photograph	Street name	Walkway width [m]	Participants count			
			Narrow	Middle size	Wide all	Wide no dual c-ways
5L	Dover Street	9	7	1		
5N	Clumber Street	10	4			
2N	Clumber Street	10	1			
16N	Broad Street	12	4	2		
10N	St Peter's Gate	13	1	3		
17N	Heathcoat Street	13	1			
9L	Haymarket	16		1		
25N	Lister Gate	16			1	1
13L	Newarke Street	16			1	1
28N	Friar Lane	17		1	1	1
4L	Granby Street	18		3	1	
6L	Rutland Street	18		3		
2L	Victoria Park Road	18		2	1	1
12L	Welford Road	20		4		
22N	Lower Parliament Street	22			3	
33N	Upper Parliament Street	23		2	1	1
1N	Upper Parliament Street	23			1	1
26N	Maid Marian Way	28			1	
3L	St George Street	30			3	

Table 7.3: Initial walkway categorisation.

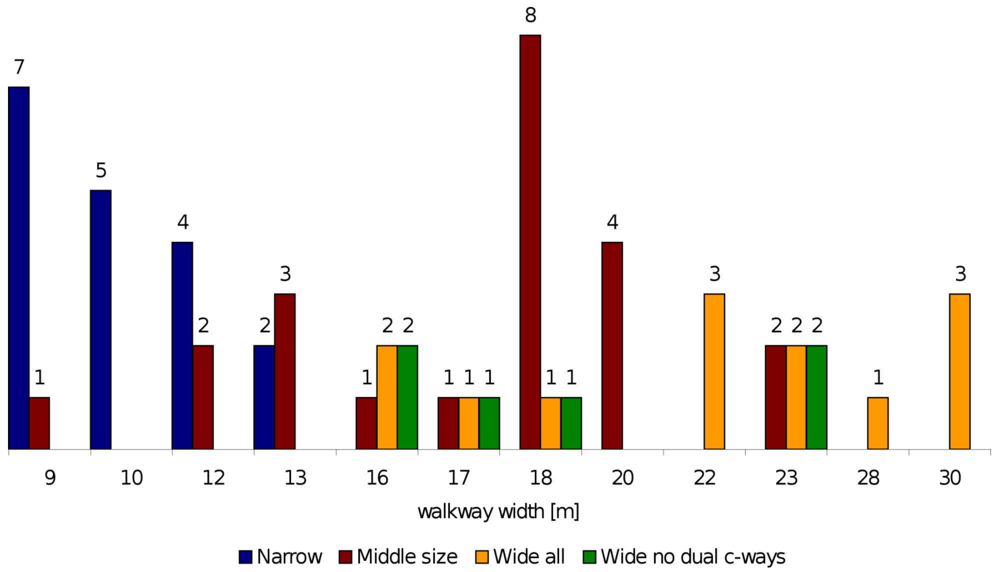

Figure 7.3: Distribution of the initial categories along the walkway width scale.

However, since dual carriageways have different effects on the selection of the evaluation route, they need to be excluded from the definition of the wide walkway category. Therefore, an additional category *Wide no dual c-ways* is defined.

Descriptive statistics (mean, standard deviation, and variance) of the initial walkway width categories distribution are reported in Table 7.4 and graphically displayed in Figure 7.4. Due to the small sample size the dividend in the Equation 7.2.1 for the standard deviation is expressed as *n-1*.

$$\sigma = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}} \tag{7.2.1}$$

Several conclusions can be suggested by visual observation of the distribution:

- Differences between the meaning of: *Narrow*, *Middle size*, and *Wide all* walkway width categories can be observed.
- The dispersion of the *Middle size* and *Wide all* categories overlap.
- *Wide all* category spreads the most around the width scale (Var = 27.8).
- There does not seem to be a significant difference between means and

Initial walkway categories	Mean	Standard deviation	Variance
Narrow	10.4	1.5	2.3
Middle size	17.0	3.6	13.3
Wide all	22.8	5.3	27.8
Wide no dual c-ways	18.8	3.3	11.0

Table 7.4: Descriptive statistics of initial walkway width categories.

distributions of *Middle size* and *Wide no dual c-ways* categories (Difference ≐ 2 m).

- The dispersion of *Middle size* and *Wide no dual c-ways* categories heavily overlap.

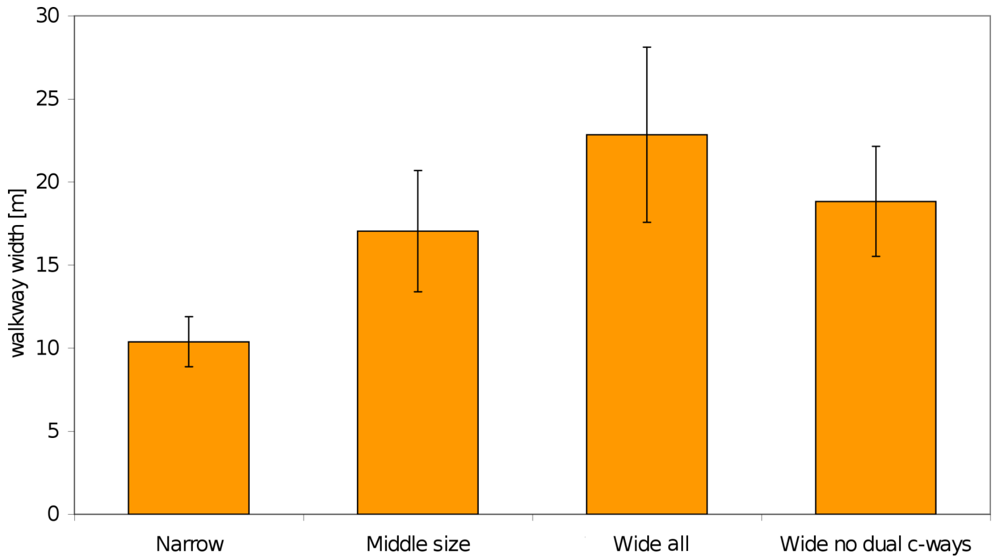

Figure 7.4: Bar chart depicting distribution of the initial walkway width categories (error bars represent ±SD).

7.2.6.2 Evaluation of the Walkway Categories

It was decided to exclude the *Wide all* category from further evaluation due to the inconsistency of the nature of the road (single and dual carriageways). To confirm the findings of the visual observation additional testing was done. The Analysis of variance (ANOVA; Ebdon, 1985) test was used to undertake more formal comparison of the categories. The null hypothesis states that:

> All three walkway width categories have equal distribution along the width scale.

The value of the test statistic F = 32.25 is greater than the critical value $F_{crit(2,43)}$ = 3.22. This implies that the null hypothesis can be at 0.05 level of significance rejected, suggesting that the difference between the walkway width categories is statistically significant.

However, ANOVA is based on following assumption:

- Observations between and within samples are random and independent.
- The observations in each category are normally distributed.
- The population variances are assumed equal (Rogerson, 2001).

The first assumption has been violated since the population sample was not selected randomly. In addition, the observations (walkway width measured values) in each category are not independent since they are often based on comparison of walkway widths on several photographs. Due to the small sample size, it cannot be determined whether the observations in each category are normally distributed. Therefore, the second assumption cannot be confirmed as valid. Finally, to identify whether the third assumption was violated an assessment of equal variance is done by computing Levene's test (Rogerson, 2001). The calculated value of the Levene's test, L = 4.84, is greater than the the critical value of $F_{2,50} = 3.19$. Hence, the assumption of equal variances is not supported. Consequently, due to the violation of all three assumptions, it was decided that the results of ANOVA test are not reliable and that additional analysis should be done before any conclusion regarding the definition of the walkway width categories was drawn.

Next, Student's t-test was conducted to assess the differences between each pair of categories. The test was run three times to evaluate all possible combinations of categories. The null hypotheses state that:

1. *Narrow* and *Middle size* categories have identical means and are equally distributed along the width scale.

2. *Narrow* and *Wide no dual c-ways* categories have identical means and are equally distributed along the width scale.

3. *Middle size* and *Wide no dual c-ways* categories have identical means and are equally distributed along the width scale.

Since the alternative hypotheses assume that the mean of the preceding category (e.g. *Narrow*) is smaller than the mean of the subsequent one (e.g. *Middle Size*) the one-tailed form of the t-test statistic was used (the change is expected only in one direction; Ebdon, 1985).

The results summarised in Table 7.5 indicate that with the exception of *Middle size* and *Wide no dual c-ways* test the calculated t-test value is greater than the critical value. Therefore, the null hypotheses can be rejected for these cases at 0.05 significance level. However, since the t_{stat} value of *Middle size* and *Wide no dual c-ways* categories is lower than the critical value, the null hypothesis cannot be rejected at the selected level of significance.

1st tested category	2nd tested category	t_{stat}	degrees of freedom	t_{crit}
Narrow	*Middle size*	7.80	23	1.71
Narrow	*Wide no dual c-ways*	6.04	5	2.01
Middle size	*Wide no dual c-ways*	1.15	8	1.86

Table 7.5: Summary of Student's t-tests applied on the walkway width categories.

Since Student's t-test is, in principle, a special case of ANOVA where two categories are compared, the same set of assumptions about the application of the test apply. Therefore, with respect to the assumptions the results cannot be proclaimed as generally valid. Nevertheless, the outcomes of the Student's t-test support the initial findings determined by the visual observation of the distribution. Hence, it cannot be determined that *Middle size* and *Wide no dual c-ways* represent different width categories since the tests indicate that the differences between the means and the distributions might be caused by chance.

Based on the above findings the number of walkway width categories was reduced into two: *Narrow* walkways and *Wide* walkways. While the final *Narrow* walkway width category contains the same data as the initial one, the *Wide* walkway width category combines together *Middle size* and *Wide no dual c-ways*. The final distribution of the categories can be seen in Figure 7.5. Table 7.6 summarises the descriptive statistics of the distributions which are further graphically displayed in Figure 7.6.

Final walkway categories	Mean	Standard deviation	Variance
Narrow	10.4	1.5	2.3
Wide	17.4	3.6	12.9

Table 7.6: Descriptive statistics of the final walkway width categories.

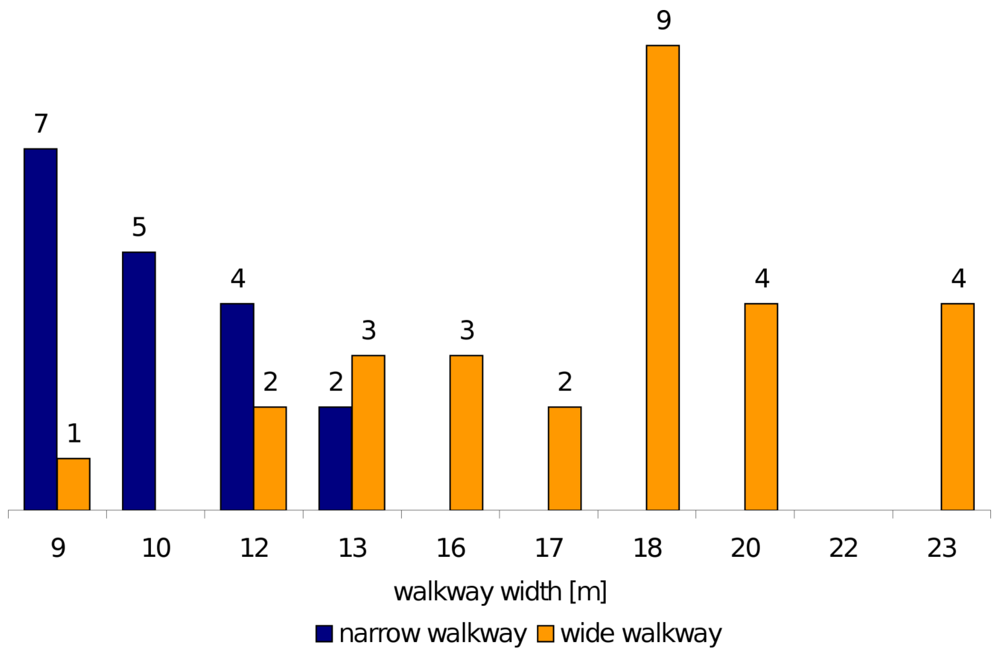

Figure 7.5: Distribution of the final categories along the walkway width scale.

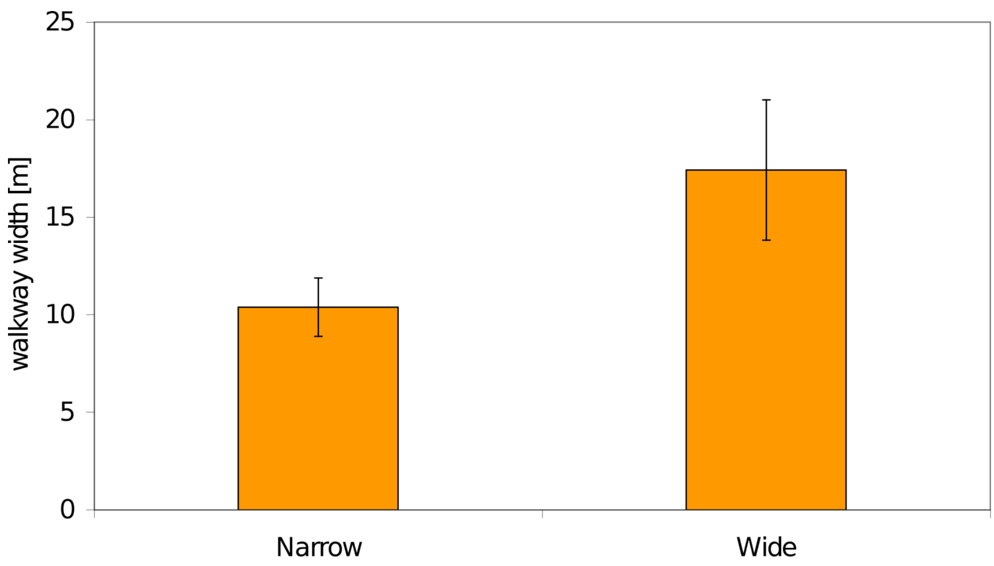

Figure 7.6: Bar chart depicting distribution of the final walkway width categories (error bars represent ±SD).

7.2.6.3 Categorising the Road Network

A clear pattern emerged from the organisation of the photographs during the PEI (Appendix J). With respect to the photographs of *dual carriage-ways* and *pedestrianised streets*, participants' decisions were directed by the number of moving cars and pedestrians in the area. Hence, the second and the third most frequently referenced factors prevailed over the road width. To acknowledge this difference in InSiM it was decided to exclude these two road types from the walkway width classification and assign them into two separate categories: *Dual carriageways* and *Pedestrian streets*. Since the characteristics depicting the nature of the road are recorded in the *natureOfRoad* attribute of ITN layer, identification of such roads within the *RoadLink* datasets was straightforward.

According to the final classification of the walkways (with respect to width) it was identified that the *Narrow walkway* category is distributed between 8 m to 12 m and the interval of the *Wide walkway* category is 13 m to 21 m. This clear differentiation can be observed in Figure 7.5 where (with exception of one case) the categories are delimited by the 12-13 m width.

Based on the above information it was decided that the final categorisation of the road network forming the simulation environment is as follows:

- **Dual carriageways** (RoadLink where natureOfRoad ="dual carriageway");
- **Pedestrianised streets** (RoadLink where natureOfRoad = "pedestrianised street");
- **Narrow walkways** (width of the walkway is $\leq 12.5m$);
- **Wide walkways** (width of the walkway is $> 12.5m$).

This means that each feature of the road network is presented (beside its geometric representation) by a single textual attribute that holds one of the above values.

7.2.6.4 Measuring Walkway Width

Approach I

Since walkway width is not included in the OSMM attribution, additional processing steps needed to be undertaken to obtain such information. Ordnance Survey (OS) was contacted for support in this matter (Thorm, 2008). As a result OS had provided a *RoadLink* dataset where minimum road width was calculated as an additional attribute. However, this information was only available for approximately 70 % of the *RoadLink* features. In addition, the values ranged gradually from 0 m to 21 m (in the Nottingham dataset). However, according to the Manual for Streets (Department for Transport, 2007, pg. 34), the minimum carriageway width is 5.5 m. Since 52 % of the RoadLink features was classified as less than 5.5 m it was concluded that this this method does not provide information of sufficient quality. Moreover, the attribute only included the width of the carriageway as opposed to the whole walkway which could, in some places (e.g. a narrow carriageway with wide pavements on each side), result in incorrect classification. Due to its incompleteness and misleading information this database was considered unsuitable.

Approach II

Each *RoadLink* in the ITN layer holds information regarding its length (*length*). In the Topographic layer of OSMM each road is represented as a polygon with an attribute regarding the extent of its surface area (*calculatedAreaValue*). In addition, each *RoadLink* contains a reference to the appropriate *Roads, tracks and paths* feature/s by which it is represented in the Topographic layer (*referenceToTopographicArea*). Therefore, based on this information, it was possible to link these two datasets together and associate each *RoadLink* with the surface area of the particular road segments. Under the assumption that each *Road* feature can be approximated to a rectangle where its length is equal to the *length* value and its surface area to *calculatedAreaValue*, it was possible to calculate the width of the *RoadLink* as a ratio of the surface area and the length. This method has several shortcomings:

- Similar to the OS provided dataset it only considers the width of a carriageway rather than the walkway.
- Difficulties arise when a *RoadLink* is associated with more than one polygon.
- Not all *Roads, tracks and paths* features can be easily approximated to a rectangle (e.g. roundabouts and other irregularly shaped areas).

Consequently this approach was also rejected.

Approach III

Since the automated approach to extraction of walkway width did not provide any satisfactory results, it was decided to obtain such information manually by using the *Measure* tool in ArcMap. Each *Roads, tracks and paths* feature in the Topographic layer holds information regarding the name of the street it represents (*roadName* attribute). Due to the existing connection between the two OSMM layers it is possible to associate the *roadName* attribute with each feature in the *RoadLink* dataset.

The following assumptions and simplifications were set to speed up the measuring process:

- The road network is classified according to name of the street.
- Each named street is measured only on one location where the width was assumed as representative for the whole street.
- The measurement is taken from "wall-to-wall" or between areas that appeared to be accessible by pedestrians (the whole walkway).
- *Dual carriageways* and *Pedestrianised streets* are excluded from the measurement.

Instead of providing the measured value of the width the results are recorded as values of the walkway category (*Narrow*: $d \leq 12.5m$; *Wide*: $d > 12.5m$).

7.2.7 Preferred Destination Representation

In addition to the road network, the simulation environment needed to include reference to areas that represent preferred destinations (see Section 6.5 for definition) towards which the agents navigate once an incident occurs. Three key locations were identified to be:

- home,
- open space at a safe distance from the incident,
- incident area.

Each of the above is represented in InSiM as a point with spatial reference to the real geographic location by a set of Ordnance Survey National Grid coordinates. The following paragraphs provide more information regarding the identification of the preferred destinations.

7.2.7.1 Home

It was assumed that the majority of the population would have their homes out of the simulation region since the extent of the simulation environment covers only the area of the city centre. Therefore, the notion of home is substituted by several locations at the edges of the simulation map by which people would exit the city centre. The actual locations of the exit points were selected using an assumption that people normally leave a city centre by public transport or car by the main transportation routes oriented towards the outskirts of the city. The exit points were approximated to four major roads each leading towards one of the four cardinal directions (North, South, East and West). Such distribution of exit points was found appropriate to prove the concept of the model.

Additional information would need to be collected in order to identify the exit points more accurately.

7.2.7.2 Open Space

The open space locations are associated with squares, parks, or other open areas (e.g. areas around cathedrals, castles, monuments, theatres, etc.) For the sake of simplicity it was decided that InSiM should contain only two such locations. These should be situated at a "reasonable" distance from the incident, since, as indicated by the interviewees, people would look for a safer place which is easy to access from their current position. It was assumed that people would not like to walk longer than 10 min. Therefore, these preferred destinations should be situated up to 500 m from the incident.

7.2.7.3 Incident area

As discussed in Section 7.2.1, the explosion in InSiM is situated in front of a large shopping centre in the centre of a city. This location was selected to represent a place where a CBRN explosion could cause serious harm[1]. For sake of simplicity InSiM does not consider any secondary explosions detonating at the same time or with a time delay.

The above information is summarised into a list of requirements (Table 7.7) according to which the actual preferred destinations for the two use cases by which InSiM was tested (further discussed in Chapter 8), were selected.

7.3 Agent Specification

An agent in InSiM represents a pedestrian who has good knowledge of the city centre. However, in real situations some people might be less familiar with

[1]Based on definition of a CBRN incident in Minister of Public Works and Government Services (2005)

Preferred destination	Representation
Home	Exit points of main transportation routes on the edge of the simulation environment located in four cardinal directions.
Open space	Open areas or generally known landmarks located within 500 m from the incident.
Incident area	Entrance to a large shopping centre located in the city centre.

Table 7.7: Requirements for selecting locations of preferred destinations.

the area than others. Nevertheless, since the experimental studies revealed that such people would be provided with assistance from others. Therefore, their representation was omitted.

Based on discussions with incident commanders (Jones and Whelan, 2007), it was decided that other parties involved in the response (e.g. emergency services) can be excluded from the model. InSiM also does not consider people that could emerge from the shopping centre or any other buildings, nor public transport passengers emerging from a bus, train or tram. It is assumed for the purpose of the simulation that such people would not have any major influence on the response behaviour nor would significantly alter the dispersion patterns of the evacuating pedestrians.

Since the interest is in observing the agent's behaviour from the global perspective, it was decided to represent each agent as a point, the movement of which is constrained by the road network.

7.3.1 Representation of Response Behaviour

The analysis of experimental data revealed that people would adopt one of the following three behaviours (see Section 6.5 for more information):

- assistance,
- evacuation,

- shock.

It was also identified that shock would only persist for a short period of time and would be followed by one of the two remaining behaviours. Therefore, it was decided to exclude the shock response from InSiM.

7.3.1.1 Assistance

Assistance can be of two forms:

- providing first aid to injured people near the incident,
- directing uninjured or "mobile casualties" towards a safer destination.

In principle, both of the assistance approaches can be understood as a form of movement (navigation) towards a specific location. While people willing to provide first aid would proceed towards the incident area to search for victims, the others would either give advice on directions or would walk with the victims towards an open space where they would await for advice from emergency services. Therefore, the assistance behaviour can be represented as *movement towards a location of preference*.

7.3.1.2 Evacuation

The evacuation behaviour, as defined by the experimental studies, is connected with immediate egress from the danger zone towards safer location which could either be near open space or home. Therefore, evacuation can be represented in InSiM in the same way as the assistance behaviour, i.e. as *movement towards a location of preference*.

7.3.1.3 Non-emergency Behaviour

Not everybody located in the city centre would be immediately aware of the incident. Since the incident awareness radius was suggested to be approximately

120 m, the number of unaware people would be, at the time of explosion, significantly larger than of the direct witnesses. Therefore, such people cannot be omitted from InSiM. It is assumed that the primary reasons for people to be walking in a city centre are: shopping, sightseeing, walking to/from work, home or entertainment (restaurant, cafe, cinema, sport facilities, etc.), or just undirected strolling through the streets. Such behaviour observed at global level, could be seen as random. Therefore, the category of these pedestrians is represented in InSiM as *random movement*. Such representation of movement is common in many agent-based models e.g. in KXPEM (Castle, 2007), where the agent chooses randomly from adjacent cells if the most preferable one is occupied, or the random movement of agents over recreational areas in crowd simulation model by Shendarkar et al., 2006, etc.

7.3.1.4 Navigation

The movement of people affected by a CBRN explosion is not chaotic but directed towards a specific destination. The factor that has the strongest effect on selecting the most appropriate route is the width of the walkway. Therefore, this factor needs to be incorporated into the algorithm that guides the navigation of the agent within the simulation space.

One possible way of representing such reasoning is to create a cost surface. Such an approach was, for instance, selected by Castle (2007) where each cell that represents a location in the tube station is associated with a specific value determining the distance of the cell from the emergency exit. The agents then navigate towards the exit by selecting cells that have the lowest cost surface value. The same approach was also used by Batty et al. (2003) where the agents move from the carnival entry points towards the location of the main event by following the most accessible path.

Since the InSiM simulation space is not represented in a cellular form, a cost surface, as it was presented in the previous two examples, cannot be implemented. However, for the network space representation a conceptually similar approach exists. In this case the "cost" is associated with each edge as its weight. For instance Shendarkar et al. (2006) assigned the weight values with respect to the level of danger each road segment is associated with once the explosion occurs. Consequently, the agents navigate on the *path of least effort*, i.e. keeping the sum of all weights minimal.

For the purposes of InSiM it was decided to use the weight-based approach where the weights represent the walkway categories as defined in Section 7.2.6.3. The agents therefore move on the simulation space by following the *path of least effort*, i.e. the route which is the most preferable for navigation. The length of an edge as it is perceived by an agent is formed by the formula presented in Equation 7.3.1, where d depicts the actual geometrical length, i depicts the road network category (narrow, wide, dual c-way, pedestrianised street) and w_i represents the weight associated with the particular category.

$$d^i_{fin} = d \cdot w_i \tag{7.3.1}$$

In total three weighted road networks are created to distinguish between the differences in navigation preferences:

- wide walkway prioritisation (WWP), where wider walkways are perceived as shorter in comparison to their actual length ($d^{wide}_{fin} < d$);
- prioritisation of narrow walkways (NWP), where narrow walkways are perceived as shorter ($d^{narrow}_{fin} < d$);
- shortest path (SP); where the characteristic of the walkway is not considered ($d_{fin} = d$).

The actual weights are summarised in Table 7.8. In this research the weights were assigned on the assumption that people would follow the preferred option unless it is perceived considerably longer than the shortest paths. However, the actual decision on when to abandon the preference is highly variable. For simplicity it was decided that the most preferable option would be perceived as 0.5 multiple of the actual length. This means that, for instance, a 4 km route would be perceived, if fully followed on preferable walkways, as 2 km long. Following the same concept, a route of the least preference is perceived by the agents as 1.5 multiple of the actual length (a 4 km route becomes a 6 km one).

Since participants reported that they would avoid crowded areas, it was decided to represent *Pedestrianised street* as the least preferable option ($d_{fin}^{PS} = d \cdot 1.5$) for both NWP and WWP. Since *Dual carriageways* are, in principle, wide, their weight (as perceived by NWP agents) is identical to the weight of the *Wide* walkways. However, due to the danger of moving traffic its weight for WWP agents is set as less preferable than for *Wide* walkways. It was identified that people with wider walkway preference dislike following narrow walkways to a greater extent than people with a preference for narrower one dislike wider walkways. This can be seen in Table 7.12 which indicates that 18 % of participants who reported a preference in narrow walkways during the course of SSI inclined more towards wider walkways when organising the photographs in PEI. This is shown in the model as the difference in weights for NWP agents and the *Wide* walkway category ($w_{WW} = 1$) and WWP agents and the *Narrow* walkway category ($w_{NW} = 1.5$).

Finally, the weights for the shortest path preference are set to 1 to represent the actual geometrical distance of the route.

Walkway category	Navigation preference weights		
	Wide (WWP)	Narrow (NWP)	Shortest path (SP)
Narrow (NW)	1.5	0.5	1.0
Wide (WW)	0.5	1.0	1.0
Dual c-way (DC)	1.0	1.5	1.0
Pedestrianised street (PS)	1.5	1.5	1.0

Table 7.8: Weights of navigation preferences.

7.3.2 Defining an Agent's Attributes and Reasoning Process

7.3.2.1 Constraints put on InSiM

The period in which the behaviour of affected people is most of interest to Nottinghamshire Fire and Rescue Service is up to 30 minutes after the blast (Jones and Whelan, 2007). The simulation needs to incorporate realistic number of agents representing pedestrians. Therefore, InSiM needs to be capable of simulating large number of agents (several thousands). To follow these requirements several assumptions and constraints were made with respect to an agent's behaviour.

- An agent can only adopt one type of emergency behaviour which will remain constant during the course of the simulation. This decision is made on the assumption that people would not, in such a short time, change their decisions.
- Any type of social or family bonds (group of friends, colleagues, parents with children, partners, etc.) are omitted. The information collected by the experimental studies was based on the assumption that the participants would be alone. If in a group, people would react to the emergency differently by trying to act in benefit of the most vulnerable companion (Mawson, 2005; Perry and Lindell, 2003). It was decided to limit the complexity of the agents' behaviour to the information collected.
- It is assumed that in such a short period of time no information about the incident would be available from the media. Therefore, any type of long distance communication, where people could receive more information

on their mobile phones, is not considered. Information regarding the incident is only passed on by meeting agents that are already aware of the explosion.

- For the sake of simplicity, it was decided to restrict the pro-activeness of an agent purely on changing from an un-aware to aware state. This decision was made based on the belief that within such a restricted amount of time people would not be able to obtain enough new knowledge nor acquire new skills to be able to make more appropriate decisions which would significantly alter their behavioural patterns.
- It was assumed that the majority of people would know the city centre and hence can follow the *path of least effort*. This was based on findings of the interviews where people reported that if unfamiliar with the environment, they would follow others or would ask for directions.

In addition, some limitations were also made to reduce the complexity of the agent's attributes:

- Energy, physical condition, severity of injuries, emotional state and any other feelings or health related characteristics of an individual are not considered. It is believed that the adrenalin which would be produced due to the unexpected danger would keep most of the people moving within the required time period.
- The threshold of severe wounds caused by a backpack bomb is approximately 45 m (FEMA, 2003, pg.4-8). When using Gaussian distribution of 8,000 agents around the city centre (see Section 8.3), only 0.4 % (Nottingham) or 0.075 % (Leicester) would fall within the fatality area. Since the position of the shopping centre in Leicester is not in the centre of the map the number is smaller in the Leicester use case. This small subset of agents would not have strong influence on the emerging behavioural patterns. Therefore, it was decided to exclude fatalities and agents suffering severe injuries from the simulation.

- The analysis of the empirical data revealed that demographic background of pedestrians in general does not influence the response behaviour. Therefore, it was found unnecessary to include such information.

7.3.3 Agent's Attributes

Attributes that characterise each agent were selected with consideration of the requirements and constraints put on InSiM. The attributes are organised in Table 7.9.

Attribute	Description	Value
Speed	Although the speed of pedestrian can vary widely it was decided to keep it constant due to such a short simulation time. The walking speed is identical with recommended speed for traffic signal timing as defined in Dewar (1992).	v = 3 km/h (approx. 0.8 m/sec)
Navigation preference	Following different navigation strategies when moving towards preferred destination.	path of least effort; shortest path
Walkway preference	Prioritisation of a specific walkway type over others.	narrow walkway; wide walkway; shortest path
State	Agent's knowledge of the incident which is reflected in adopted behaviour.	aware; unaware
Preferred destination	Location towards which the agent navigates once aware of the incident.	home; open space; incident area

Table 7.9: Summary of agent's attributes.

7.3.3.1 Selecting Reasoning Mechanism

According to Castle and Longley (2005) the choice of the level of detail implemented in the model depends on the trade-offs that must be made in order to maintain realistic computing power when processing large amounts of data. Since the aim of InSiM is to identify dispersion patterns of the incident victims the number of agents and the extent of the environment are essential to the simulation and cannot be compromised. As previously discussed compromises were made with respect to the complexity of the environment representation resulting in simplifying the complex geographic space into a network holding a single attribute (walkway category). In addition, simplifications were made to the representation of behaviour and characteristics of an agent.

Since the interest is not in observing local behaviour between agents, action selection mechanisms that take into account low level interactions e.g. obstacle avoidance (Ulicny and Thalmann, 2002), or incorporate dynamic information through vision (Pan et al., 2007), would act at an unnecessarily low level of detail. Therefore, complex reasoning mechanisms that include several hierarchical tiers (hierarchical state machine: El Rhalibi and Taleb-Bendiab, 2006; force field model: Henein and White, 2007; fuzzy logic: Banarjee et al., 2005) were considered as unsuitable for use within this research.

Due to such short time period being simulated, it was decided that agents would not be able to change their decision regarding their navigation preferences or preferred destination. Moreover, the experimental studies also revealed that in emergencies, people do not reconsider their decision because it would slow them down. Therefore, application of the Belief-Desire-Intention (BDI) model (e.g. Buford et al., 2006; Shendarkar et al., 2006), where each agent is forced to deliberate about the most suitable plan and, if necessary, adopt a new one if the situation changes, was found to be inappropriate for the purposes of InSiM.

It was identified that, in general, people were more reluctant to move towards a crowded area. In addition, participants reported that they would follow others only when unfamiliar with the area. For such reasons Ant Colony Optimisation (ACO) (e.g. Batty et al., 2003; Banarjee et al., 2005) was identified as unsuitable since it seeks to find the single most optimal path from one location to another through following paths selected by other agents.

The final two reasoning approaches discussed in the literature review (Section 2.3.2.4) are finite state machines (FSM) and rule-based systems (RBS). In principle, FSM do not pose any obvious problems which would challenge its implementation in InSiM. However, since the InSiM agents can only be associated with two states: unaware and aware of the incident, it was found unnecessary to organise the reasoning process in such way. Since the number of situations that need to be implemented in InSiM is very limited (random movement, navigation towards preferred destination), and due to the fact that these actions are mutually exclusive[2], it was decided to implement InSiM as a rule-based system.

7.4 General Model Characteristics

7.4.1 Number of Agents

It is preferable to set the number of agents in InSiM to correspond with the number of people that would be present in the city centre during the time of the blast. The approximate number of pedestrians can be obtained by measuring pedestrian flows through several different streets in the city centre (e.g. Le, 2007). The date, time, and period of measurement can be then associated with the time of the blast. However, the biggest shortcoming of this method is that several measurements would need to be taken at the same time to cover the pedestrian flows at different locations. This was not possible due to the restricted amount of resources for this research.

Due to the large variability of pedestrian flows in the city centre (depending on time of the year, day, hour, weather, etc.) it was decided not to specify on exact time of the explosion and use approximate estimates instead to represent a "common situation". The official tourism website of Nottingham (Visit Nottingham, 2009) reports that approximately 25 million shoppers visit Not-

[2]assumptions for selecting RBS as an action selection mechanism (proposed by Bryson, 2004)

tingham during a year. Under the assumption that shops are open 365 days a year this number could be approximated to 68,000 shoppers a day. Since most of the shops in the UK are opened 8 hours a day (9:00AM - 5:00PM), the number of shoppers can be roughly distributed over the eight hour period resulting in approximately 8,000 shoppers/hour. Therefore, it was decided to populate the simulation model with 8,000 agents as an acceptable approximation.

7.4.2 Input and Output Data

The input data for InSiM are organised into thee different layers, depending on the format of the data and their context:

- road network (geographic network);
- preferred target destinations (points);
- agents (points);

With respect to the requirements provided by Nottinghamshire incident commanders, the times of interest in which the information should be collected are 15 min and 30 min after the explosion. Therefore, locations of agents in the form of the Ordnance Survey National Grid coordinates in these time intervals need to be collected in each simulation run. To provide a means for evaluating the behaviour of a single agent it was necessary to also distinguish each agent by a unique ID number. In addition, to be able to identify how many agents become affected by the incident, it was found useful to also record the state of the agent in the output data of the simulation.

7.4.3 Distribution of Agent Categories in InSiM

The distribution of agents among the preferred destinations was defined in InSiM in correspondence with the preferences of the interviewed population sample (Table 7.10).

Preferred destinations	Distribution of agents [%]
Home	46
Open space	37
Incident area	17

Table 7.10: Distribution of agents among preferred destinations.

Similarly, the distribution of agents among navigation preferences was guided by the findings of the experimental studies presented in the contingency table; Table 7.11. The transcripts that signify the categorisation are reported in Appendix K. Since the *Middle size* walkway was found to be redundant, participants referencing this category were evenly distributed between the *Wide* and *Narrow* categories (applies only for SSI).

The distribution of the interviewed population sample with respect to the navigation preferences is presented in Table 7.12. The first two columns represent the distribution in absolute values depicting the final counts from the contingency table. The following two columns represent the values as relative frequencies. The last column depicts the final distribution calculated as the average since the contribution of both studies is considered equal.

Participant		SSI			PEI		
	Middle size	Wide	Narrow	Shortest	Wide	Narrow	Shortest
P3	n/a	n/a	n/a	n/a	1		
P4		1			1		
N01	1				1		
N02	1						1
N03			1			1	
N05			1			1	
N06		1			1		
N07				1	1		
N08	n/a	n/a	n/a	n/a	1		
N09			1				1
N10	1				1		
N11		1			1		
N12	n/a	n/a	n/a	n/a	1		
N13		1			1		
L02		1			1		
L03				1	1		
L04			1		1		
L05		1			1		
L06	n/a	n/a	n/a	n/a	1		
L07				1	n/a	n/a	n/a
L08		1				1	
L09			1			1	
L10		1			1		
L11	1				1		
Total	4	8	5	3	17	4	2
Excluding Middle size	n/a	10	7	3	17	4	2

Table 7.11: Navigational preferences of participants.

Navigation preference	SSI	PEI	SSI [%]	PEI [%]	Final distribution [%]
Narrow	7	4	35	17	26
Wide	10	17	50	74	62
Shortest path	3	2	15	9	12

Table 7.12: Distribution of agents among the navigation preferences.

Human Behaviour Representation	Human Behaviour Parameterisation	Environment Representation	Sense of Space and Place	Reasoning Process	General
Aware agents	Speed (3 km/h)	Roads (geographic network model)	Navigation (random movement; shortest path; path of least effort)	Rule-based system	Number of agents (8,000)
Unaware agents	Navigation preference (path of least effort; shortest path)	Preferred destinations (point data model; home, open space, incident area)	Walkway category (narrow walkway; wide walkway; dual c-way; pedestrianised street)		input data (road network; target destinations; location of agents)
	Walkway preference (narrow walkway; wide walkway; shortest path)	extent (3km x 3km)			output data (ID and locations of agents at 0 min, 15 min and 30 min)
	State (aware; unaware)	selected location (city centre)			distribution of preferred destinations (home: 46 %; open space 37 %; incident area 17%)
	Preferred destination (home; open space; incident area)	incident (point data model; large shopping centre in a central area of a city)			distribution of walkway preferences (narrow: 26 %; wide 62 %; shortest path 12 %)

Table 7.13: Key characteristics of InSiM.

7.5 Chapter Summary

The aim of this chapter was to define the conceptual model of InSiM. Each decision was explained and the evidence as to the basis on which the decision was made given. The key components and characteristics are organised in Table 7.13 according to the three relevant aspects related to development of a geosimulation model out of the five aspects defined in the literature review. These three aspects are:

- *Human Behaviour Representation & Parameterisation*,
- *Environment Representation & Sense of Space and Place*,
- *Reasoning Process*.

The *Understanding the Application Domain* aspect was already addressed in Chapter 4 and the last aspect *Result Analysis & Model Evaluation* is discussed in Chapter 9.

The information collected in this chapter guides the implementation of InSiM as discussed in the following Chapter 8.

Chapter 8

Agent-based Model Implementation & Case Studies

8.1 Introduction

The purpose of this chapter is to provide a formal description of InSiM structure. The model key components are defined according to the conceptual model presented in the previous chapter. The chapter is organised as follows. Section 8.2.1 contains definition of three model configurations that are used to test how incorporation of real-life information affects the simulation results. The following sections (8.2.2 - 8.2.6) provide an operational overview of InSiM through description of the key classes and processes supporting the simulation. The key behavioural algorithms are described with use of pseudo code, the simulation processes as activity diagrams, and the information and data streams as a data flow diagram. This chapter concludes with definition of two case studies by which the InSiM implementation is tested (Section 8.3).

8.2 InSiM Implementation

The following sections provide a description of the InSiM configurations and implementation. The text introduces the key InSiM components that are related to the representation of the agent's behaviour.

8.2.1 InSiM Configurations

Three configurations of InSiM were used to test to which extent incorporation of information collected by the experimental studies influences the simulation outputs. The first configuration represents a *base model* where no real-life information is used for definition of the agent's behaviour. The second and third configurations then gradually incorporate the knowledge obtained through collection and analysis of the empirical data. The effects of the richer and more complex agent reasoning is measured by comparing the simulation outputs against each other in the next chapter. The three configurations are:

- Configuration I: Random movement (RAM)
- Configuration II: Behaviourally enhanced movement (BEM)
- Configuration III: Spatially aware movement (SAM)

The three configurations in principle represent sequential process in which each iteration extends the preceding one by additional knowledge. More detailed description of each configuration is provided in following paragraphs.

8.2.1.1 Configuration I: Random Movement

In the first iteration of the model all agents move around the city centre without any specific goal. This configuration does not incorporate any knowledge collected by the experimental studies and hence represents "naive" behaviour. This behaviour was defined based on a simple assumption that people would not change their behaviour once an incident occurs. This configuration serves as a *base model* against which the other two more advanced models are tested to identify to what degree the additionally implemented knowledge affects the emerging patterns of the agents distribution among the simulation environment.

Algorithm 8.1 Pseudo code of RAM agent behaviour in one simulation step.

```
1:  nodes = get nodes of the current edge
2:  select a node from nodes not associated with edge in edge history tenure
3:  remaining distance = max move distance
4:  repeat
5:    calculate distance from current position to the selected node
6:    if remaining distance > calculated distance then
7:      remaining distance = remaining distance − calculated distance
8:      total distance = total distance + calculated distance
9:      move to the node
10:     get edges connected with the node
11:     if only one edge exists then
12:       clear edge history tenure // dead end
13:     end if
14:     randomly select edge from the connected edges excluding edges in the
        edge history tenure
15:     calculate length of the edge
16:     calculated distance = length of the edge
17:     put the edge into edge history tenure
18:   else
19:     walk remaining distance
20:     set current position
21:     remaining distance = 0
22:     put the edge into edge history tenure
23:   end if
24: until remaining distance > 0
```

To stop the agent from "oscillating" between two crossroads the behaviour is implemented as a pseudo random movement (inspired by Mysore et al., 2006). In this behaviour an agent remembers edges that have been visited in the last n simulation steps. The reference to these edges is kept in the *edge history tenure* (line 2 in Algorithm 8.1). Once an agent reaches a node (crossroad) it assesses whether any of the edges leading out of the node had been recently visited. If yes, the edge is excluded from selection. Consequently, the agent randomly picks from the remaining edges one which is to be followed in the subsequent simulation step. An exception is a situation where agent reaches a dead end (line 11). The behaviour is explained in more detail in pseudo code depicted in Algorithm 8.1.

8.2.1.2 Configuration II: Behaviourally Enhanced Movement

This configuration enhances RAM by incorporating knowledge related to human response behaviour as it was defined in Section 7.3.1. This means that the agents are categorised into three groups according their choice of preferred destination (i.e. *home*, *open space*, *incident area*) as defined in the conceptual model.

The response behaviour would be adopted only after information regarding the incident is obtained. Therefore, agents that have not:

- been in contact with the incident, or
- met agents who already are aware of the incident

remain moving in the same way as defined in RAM configuration. This effectively divides the agent population into two behavioural categories:

- AWARE agents
- UNAWARE agents

The AWARE agent is following the *shortest path* towards the preferred destination. The influence of the environment on the route selection is in this configuration omitted. Pseudo code which captures one simulation step of an AWARE agent is depicted in Algorithm 8.2.

8.2.1.3 Configuration III: Spatially Aware Movement

The final configuration enhances behaviour of the AWARE agent of additional spatial considerations as defined in Section 7.3.1.4. This means that agent navigates towards the preferred destination on roads which are perceived as safer, i.e. following the *path of least effort*. With respect to the conceptual model three general preferences were defined:

Algorithm 8.2 Pseudo code of AWARE agent behaviour in one simulation step of BEM configuration.

```
1: if number of already visited nodes ≥ number of nodes in the shortest path then
2:    do nothing
3: end if
4: remaining distance = max move distance
5: while remaining distance > 0 && number of already visited nodes < number of nodes in the path do
6:    get next node in the path
7:    calculate length between current position and the node
8:    if remaining distance > calculated length then
9:       remaining distance = remaining distance - calculated length
10:      set current position at the end node of the edge
11:      if all nodes in the path have been already visited then
12:         remaining distance = 0
13:      else
14:         get next node in the path
15:         calculate length of the edge
16:      end if
17:   else
18:      move on the edge in remaining distance
19:      current position = new position on the edge
20:      remaining distance = 0
21:   end if
22: end while
```

- wide walkway prioritisation,
- prioritisation of narrow walkways,
- shortest path.

The distribution of agents among these categories is done in accordance with the findings of the experimental data analysis. The algorithm that the AWARE agent follows is almost identical to Algorithm 8.2. The only difference is that the *length of edges* (as calculated in lines 11 and 19) is multiplied by a weight which corresponds to the particular road type as defined for the agent preference category (the weights are represented in Table 7.8). Hence the path does not correspond to the *shortest path* (line 4) but to the *path of least effort*.

8.2.2 Development Environment

Each agent can be seen as an autonomous unit without any centralised control (Maes, 1994). Therefore, the object-oriented paradigm is a very suitable medium for the implementation of agent-based models due to its modular structure (Castle, 2007). InSiM is implemented in Java since it is the object-oriented language that was used for development of the CGSagent framework. To enable further extensibility and broader applicability of InSiM its structure complies with existing standards; CGSagent (consequently InSiM) uses GeoTools (GeoTools, 2009) and JTS Topology Suite (Vivid Solutions, Inc., 2009) open source libraries which are developed to Open Geospatial Consortium (OGC) specifications. The full InSiM code can be found in an Electronic Appendix I.

8.2.3 Overview of InSiM

The InSiM classes that are associated with an agent's behaviour are depicted in the class diagram in Figure 8.1. These are also the classes that have been implemented on the top of the existing CGSagent framework (with the exception of the *Agent* interface which is presented in the diagram for completeness). To keep the diagram as transparent as possible each class only contains attributes and methods that are relevant to the agent's behaviour.

The polymorphism of the object-oriented approach is clearly visible in the definition of the different agent types; the AWARE agent is represented by class *PathMoveAgent* while the UNAWARE agent is defined in the *RandomMoveAgent*. The additional class *CBRNAgent* is implemented as a mediate abstraction step between the two very specific classes and the abstract representation of an agent (*Agent* interface). *CBRNAgent* class holds information regarding the state of the agent: AWARE or UNAWARE. This information is InSiM specific, hence it is not included in the general interface. With respect to the agent's state the specific class where the corresponding behavioural methods are defined is called

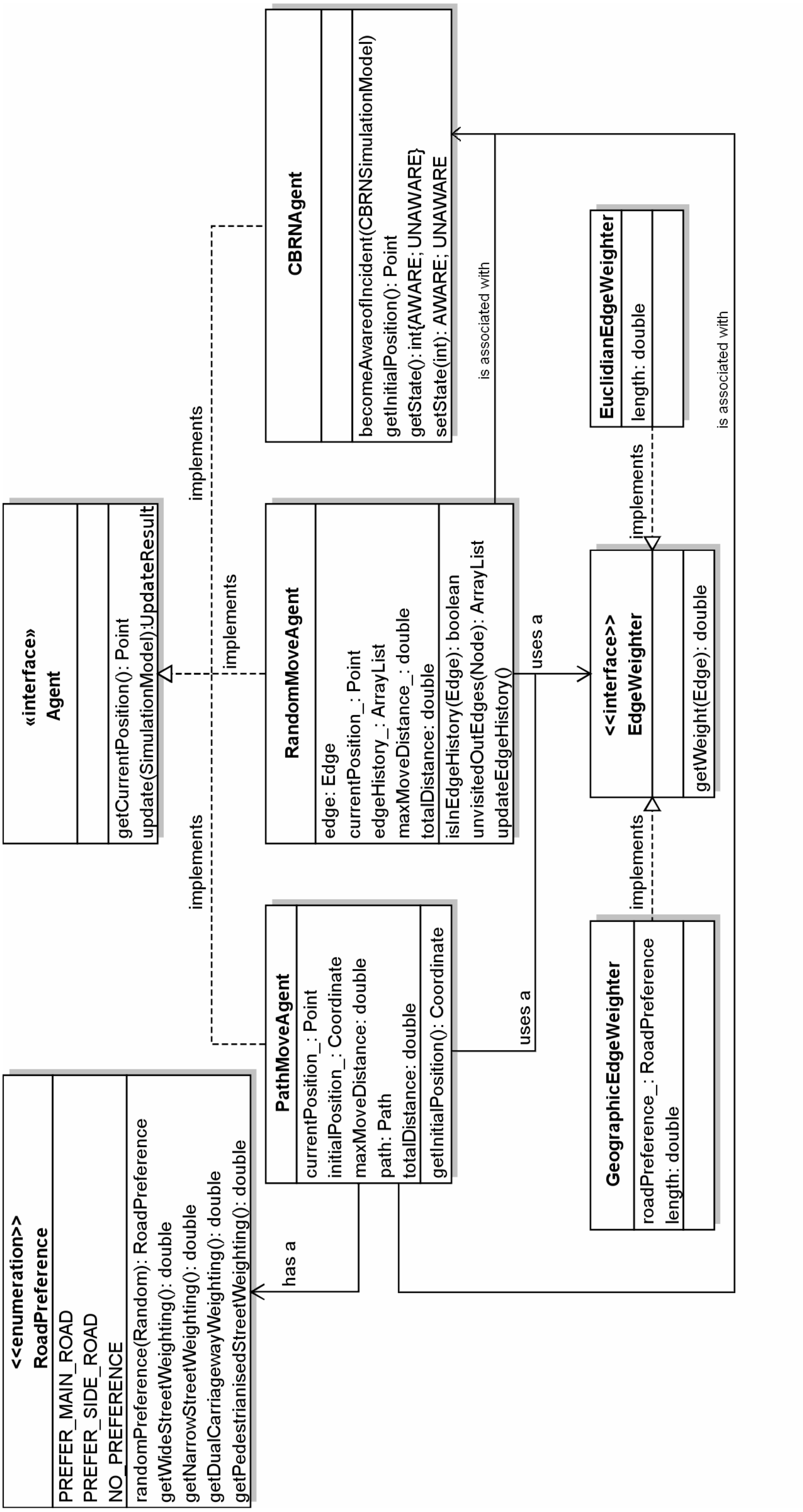

Figure 8.1: Class diagram depicting key InSiM components related to agent's behaviour.

(*PathMoveAgent* or *RandomMoveAgent*) . The classes representing an agent inherit the *update* method which depicts what happens in one simulation step as described in Algorithms 8.1 and 8.2.

Since the AWARE agent navigates through space by taking into account the different road categories, it is accessing methods from *RoadPreference* class which includes the corresponding weights. The calculation of the navigation path is done by using one of the two classes implementing *EdgeWeighter* interface: *EuclidianEdgeWeighter* for BEM configuration (shortest path) and *GeographicEdgeWeighter* for SAM configuration (path of least effort).

Figure 8.2 shows an activity diagram depicting initialisation of InSiM. This process is separated from the actual simulation run to enable the user to browse through the view and make any changes (e.g. adjusting values of some of the model parameters) without commencing the computation. The simulation begins once the Start/Run one step button is clicked (see Figure 8.3 b)). Unless the Pause/Stop button is pressed or the specified time limit has been reached, the program iterates through the agents and calls their update method.

The model key parameters are depicted in Table 8.1 together with their short description and data type they represent. These parameters can be adjusted by the user to represent different scenarios (e.g. altering number of agents, walking speed, the road network, etc.).

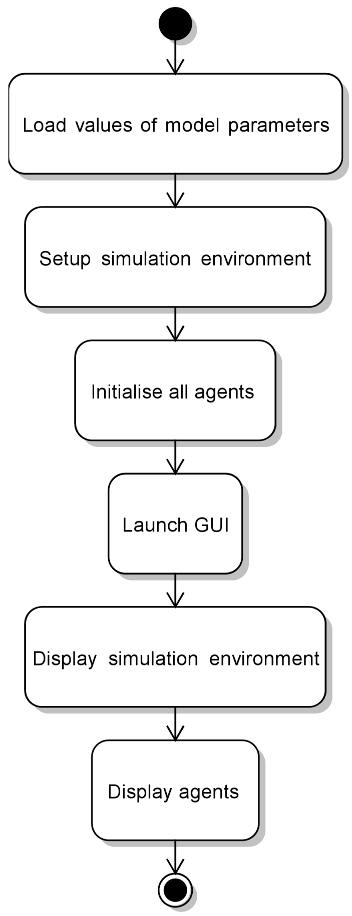

Figure 8.2: Activity diagram depicting initialisation of InSiM.

Parameter	Description	Type
incidentPosition	coordinates of the incident location	Point
randomSeed	a number used to initialise a pseudo random number generator	long
numAgents	number of agents in the simulation	int
maxSimulationDurationInMinutes	the maximum length of the simulation (in minutes)	double
agentMaxMovementKilometersPerHour	agent's walking speed (in km/h)	double
simulationSecondsPerTick	number of seconds represented in one simulation step (sec)	int
randomAgentEdgeHistoryTenure	number of last visited edges unaware agent remembers	int
incidentAwarenessRadius	distance within which agent recognises the incident (in meters)	double
agentCommunicateIncidentDistance	distance within which agents can exchange information regarding the incident (in meters)	double

Table 8.1: Key model parameters.

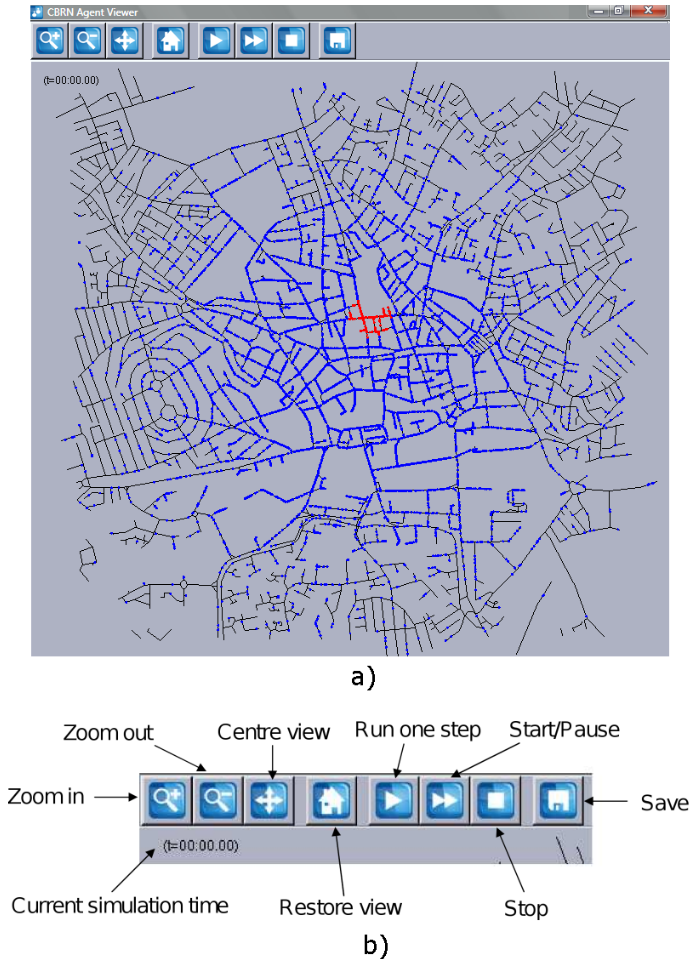

Figure 8.3: InSiM graphical user interface.

8.2.4 Graphical User Interface

Once the initialisation process is completed the InSiM graphical user interface (GUI) is launched together with the visual display of the environment and the distribution of agents on the road network (Figure 8.3 a). The view depicts the situation at the time of explosion. The road network is represented as black lines. The blue points represent UNAWARE agents and the red points agents who had been located within the *incidentAwarnessRadius* at the time of the explosion. Hence their state has been setup to AWARE. The menu bar is displayed at the top of the view together with a clock that indicates the simulation time. A closeup of the menu bar is provided in Figure 8.3 b) and further description of each button is given in Table 8.2.

Zoom in	magnify view at the location of mouse click
Zoom out	reduce the magnification level at the location of mouse click
Centre view	centre the view at the location of mouse click
Restore view	restore the original view
Run one step	execute one simulation step
Start/Pause	start the simulation, iterate continuously until the maximum simulation time is reached or the simulation is paused; second click will commence the simulation at the consequent simulation step
Stop	stop simulation after completing current simulation step
Save	save output of the simulation
Current simulation time	indicates how long the simulation is running; iterates at the *simulationSecondsPerTick* time interval

Table 8.2: Description of InSiM graphical user interface functions.

8.2.5 Implementing Influence of the Incident

The influence on the incident is depicted in InSiM by adopting emergency behaviour which is represented in the AWARE agent state. However, as Figure 8.3 a) illustrates, the majority of agents are, at the beginning of the simulation, in the UNAWARE state. An agent becomes aware of the incident if one of the two following conditions is fulfilled:

- agent moves within the incident awareness area delimited by the *incidentAwarenessRadius*, or
- agent obtains information regarding the explosion from an AWARE agent passing within *agentCommunicateIncidentDistance*.

The process of changing from UNAWARE to AWARE state is depicted in Algorithm 8.3. In addition, processes of one simulation step of AWARE and UNAWARE agents are captured as activity diagrams in Figures 8.4 and 8.5. While behaviour of AWARE agents is relatively straightforward, an UNAWARE agent has to first check whether one of the two preceding conditions apply.

8.2.6 Data Input and Output

Parameters that are related to data input and output (IO) are described in Table 8.3. The road network which represents the simulation environment in InSiM is generated from the Shape file holding features of the pre-processed ITN layer

Algorithm 8.3 Pseudocode depicting change in agent's state from UNAWARE to AWARE.

```
if agent state is UNAWARE then
    if within incident awareness radius then
        find path of least effort towards the preferred destination
        state = AWARE
    end if
    for all AWARE agents do
        get position of the AWARE agent
        calculate minimum distance between the AWARE agent and this UNAWARE agent
        if calculated distance < agent communication distance then
            find path of least effort towards the preferred destination
            state = AWARE
        end if
    end for
end if
```

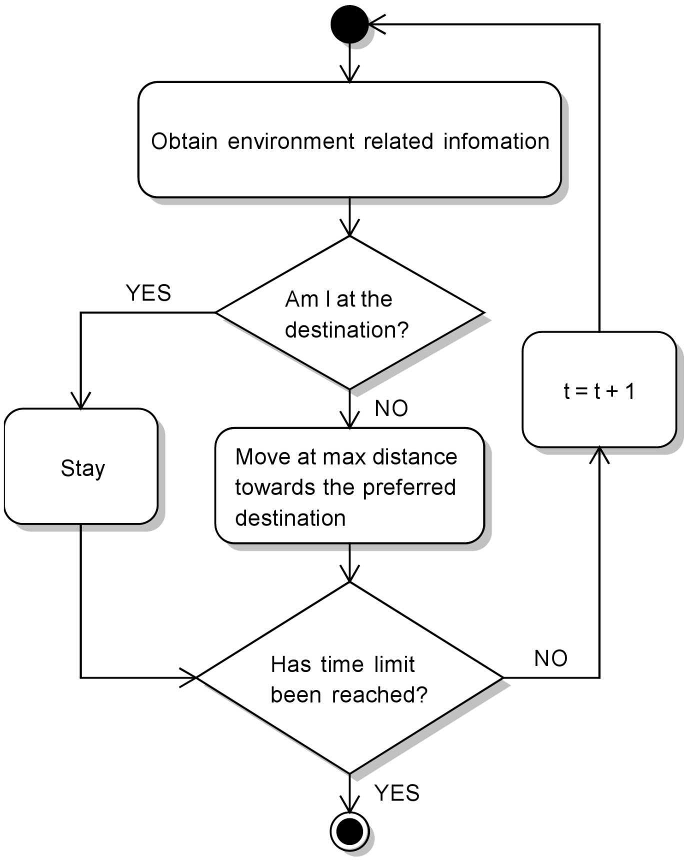

Figure 8.4: Activity diagram depicting single simulation step of AWARE agent.

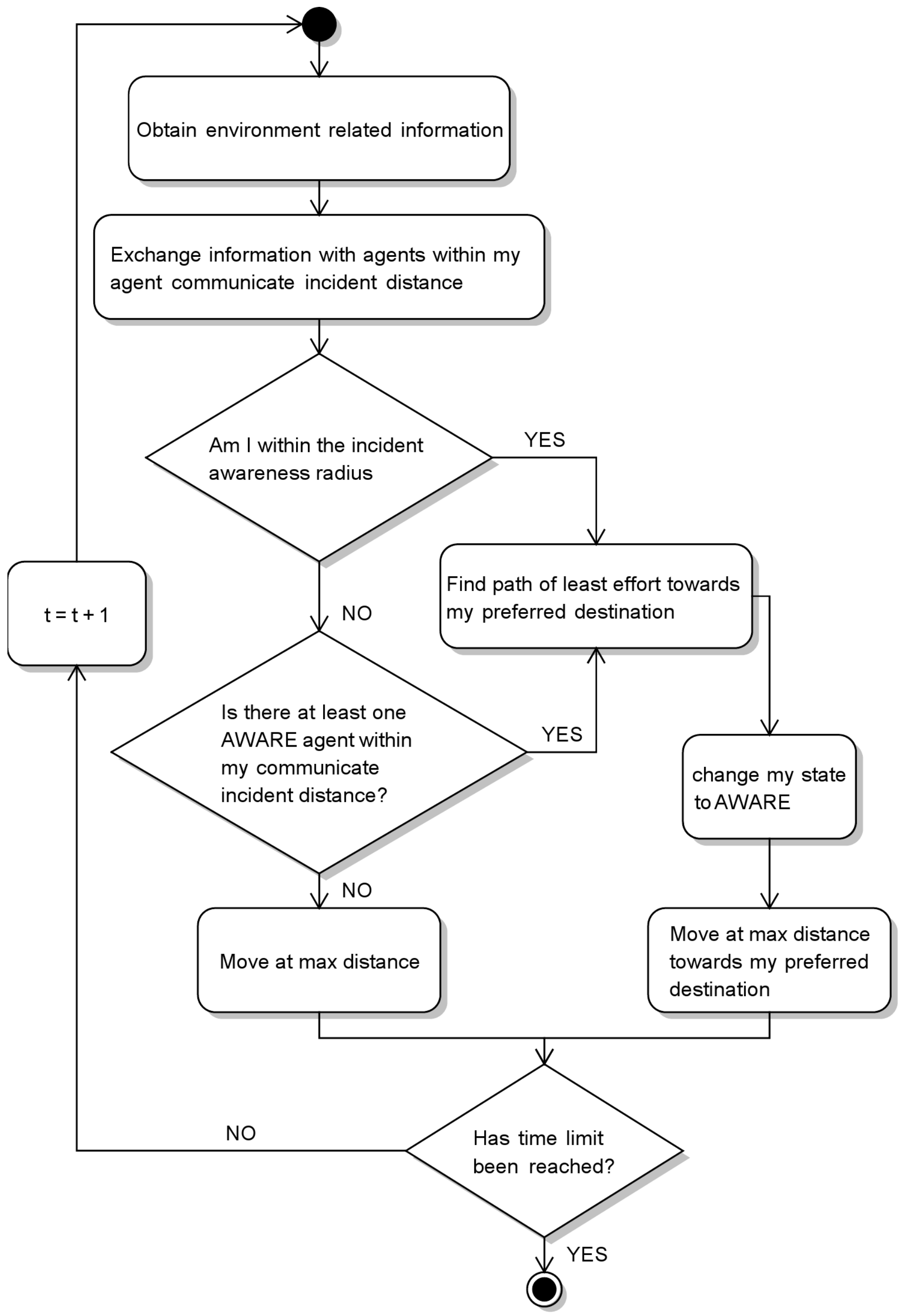

Figure 8.5: Activity diagram depicting single simulation step of UNAWARE agent.

```
                                          targetsNottingham.txt
456951,341340,11
458018,338362,11
455781,339789,12
458820,339134,12
457106,339920,19
457134,340081,18
457382,340099,17
```

Figure 8.6: Example of *targetsNottingham.txt* input file.

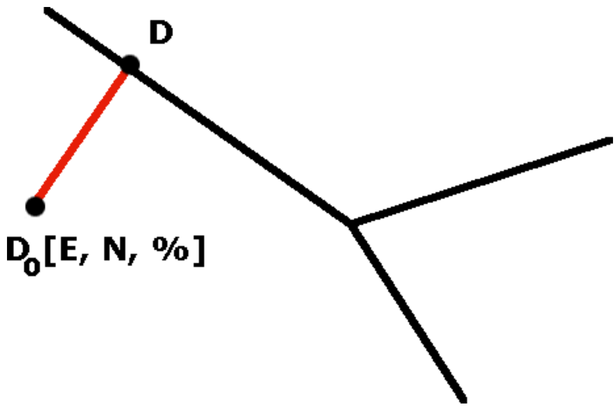

Figure 8.7: Association of preferred destination with the road network.

of OS Master Map (as indicated in Section 7.2). However, this is not the only data file that serves as an input to InSiM. The specification of symbology which is used for representation of agents is defined in an *agent.sld* file as an XML Schema using the OCG Web Map Service Encoding Standard (OGC, 2009).

The exact locations of the preferred destination are defined in the *preferred-Destinations* file as comma separated values (CSV) in a form of: National Grid coordinates and the percentage of agents selecting this location as a preferred destination (example is provided in Figure 8.6). The coordinates are rounded to the nearest meter. Since the locations of the preferred destinations (D_0; Figure 8.7) do not form nodes of the road network the position is associated with the closest location on the network edge. Hence, the navigation path is calculated towards the transformed location (D).

The output of the simulation is generated once the *Save* button is clicked. The results are stored into following four text files:

- *initialPositions*: file holding IDs and coordinates of all agents at the beginning of the simulation.
- *finalPositions*: file holding IDs and coordinates of all agents after the last executed simulation step.

Parameter	Description	File type
staticShapefileName	name of the shape file holding the road network data	shape
agentSldName	file defining presentation of the agent on the simulation environment	XML
agentTargetPositionsName	name of the file holding coordinates of the preferred destinations	CSV
initialPositionName	file to which the initial positions of agents are saved	CSV
finalPositionName	file to which the final positions of agents are saved	CSV
awareAgentsFinalPositionName	file to which the final positions of agents aware of the incident are saved	CSV
agentsTotalDistanceName	file to which the distance walked on the road network is saved	CSV

Table 8.3: Key IO parameters.

- *awareAgentFinalPositions*: file holding IDs and coordinates only of agents at AWARE state.
- *agentTotalDistanceName*: file holding IDs of all agents and the distances they walked on the road network during the course of the simulation.

All of the four output files use CSV format. Figure 8.9 contains example of an *initialPositions* file where the first number depicts the agent's ID, followed by National Grid coordinates. The same structure applies for the *finalPositions* and *awareAgentFinalPositions* files. Figure 8.8 contains an example of *agentTotalDistanceName* file where the measured distance is preceded by the agent's ID number. The data flow is graphically displayed in Figure 8.10 and the process of generating the output files is depicted in activity diagram in Figure 8.11.

```
                                    agentTotalDistanceName.txt
ID,NetworkDistance
0,308.6237390564706
1,649.6961652793957
2,162.45916645340566
3,2125.533426030801
4,357.06850237473634
5,827.0350528995563
6,1549.2684465355217
7,2380.79137403235
8,541.5569855857989
9,1365.2921570046917
10,750.2952482505787
11,1039.3801947577585
12,272.011509915482
13,1070.1004662327307
14,1028.3648727823738
15,1856.0688387590556
16,667.8112010740707
17,1142.131343501209
18,1135.0539953153136
19,794.9331405260695
20,863.9585426436028
...
```

Figure 8.8: Example of *agentTotalDistanceName.txt* output format.

```
                                        initialPositions.txt
ID,Xcoord,Ycoord
0,457391.39501591376,340096.44723532733
1,457585.86582233675,340266.1341776635
2,457465.88678790006,338844.2358484873
3,456899.8422191957,339605.6954933723
4,458294.20811655687,340899.4393340404
5,457601.46193205845,339728.1554904467
6,456986.8550853366,339617.2718212669
7,457159.929554058,340011.5853060612
8,456837.91794735007,339802.70540612546
9,457528.7375125815,339311.11654924584
10,456762.0302166188,340179.9328033644
11,457718.1014064872,340471.9459165408
12,457369.52260919334,339873.90481863625
13,457566.68352033873,339267.2247865464
14,457023.6656590599,340517.5812547519
15,457958.9642406986,339820.9675430018
16,457761.17773337953,340603.3523999804
17,457709.2202570129,339463.2399432369
18,457712.5731549589,339290.54669900733
19,456796.48486224207,339798.2865301423
20,456921.9356117315,339065.18715065817
...
```

Figure 8.9: Example of *initialPositions.txt* output format.

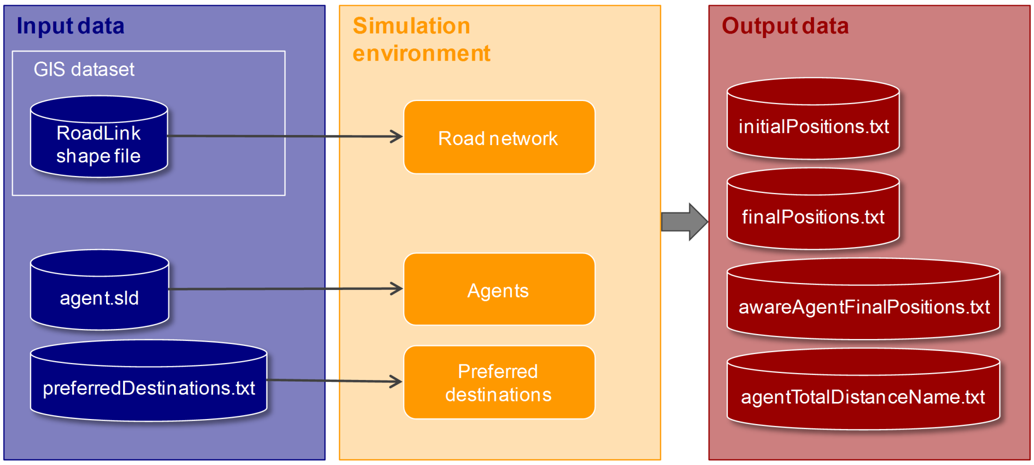

Figure 8.10: Data flow diagram.

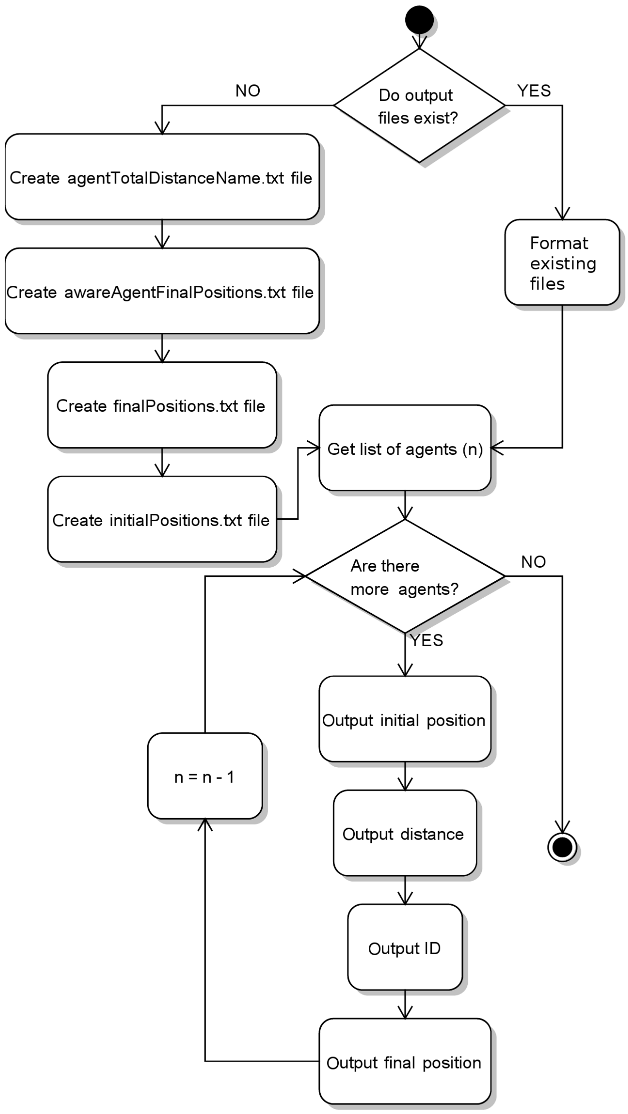

Figure 8.11: Activity diagram depicting output of a typical simulation run of InSiM.

8.3 Case Studies

The implementation of InSiM is tested through two case studies. The simulation environment is generated from ITN layers depicting Nottingham and Leicester city centres to correspond with the locations of the experimental studies. The values of the key model parameters are defined in Table 8.4. To enable comparison of the results the parameters are set the same for both case studies. The reasons for defining values of the majority of the parameters have been already provided in Chapter 7 and the remaining are discussed in the following text.

The random number generator is used for distributing agents in the simulation environment at the model initialisation step. In InSiM a Gaussian distribution around the map centre is used for placing the agents on the road network. By setting up the random seed value as an arbitrary constant, the distribution of the agents always remains the same (Knuth, 1997). This ensures that the initial conditions of all simulations will be constant.

Since it is assumed that the streets would become noisy and chaotic, the communication distance between agent was setup at maximum 10 meters. This means that UNAWARE agent can obtain information regarding the incident from agents that are in the current simulation step located within a circle of 10 m radius. Agents can only remember edges that were visited in last 10 simulation steps representing 1 real-time minute. This means that once reaching a crossroad with such a street, it is automatically excluded from the UNAWARE agent's navigation options.

The *SimulationSecondsPerTick* paramter specifies what time period one simulation step represents. For the purposes of the case studies the value was set to 5. This means that one simulation step represents 5 real-time seconds. Hence, in one simulation step the maximum distance an agent can move is 4 meters at a speed of 3 km/h (converted to approximately 0.8 m/s; resulting in 0.8 ·

Parameter	Nottingham	Leicester
staticShapefileName	lineSegmentsNotts.shp	lineSegmentsLeic.shp
incidentPosition	[457382; 340099]	[458498; 304788]
agentSldName	agent.sld	agent.sld
agentTargetPositionsName	targetNottingham.txt	targetLeicester.txt
randomSeed	1234	1234
numAgents	8,000	8,000
maxSimulationDurationInMinutes	15 min, 30 min	15 min, 30 min
agentMaxMovementKilometersPerHour	3 km/h	3 km/h
simulationSecondsPerTick	5 sec	5 sec
randomAgentEdgeHistoryTenure	10	10
incidentAwarenessRadius	120 m	120 m
agentCommunicateIncidentDistance	10 m	10 m
ModelType	RAM, BEM, SAM configurations	RAM, BEM, SAM configurations

Table 8.4: Values of key model parameters for both case studies.

$5 \doteq 4$ m/simulation step). Setting the *simulationSecondsPerTick* = 5 sec and the *agentCommunicateIncidentDistance* = 10 m will ensure that two agents who are walking against each other will always be given an opportunity to exchange information and not pass each other without knowing.

8.3.1 Preferred Destinations

The last set of parameters that remain to be defined for both case studies are the locations of the preferred destinations. Their selections and approximate position on the simulation environment are discussed in following paragraphs.

8.3.1.1 Nottingham

In this case study the explosion is simulated at one of the two main exits to the Victoria Shopping Centre [1] heading towards the Lower Parliament Street. The direction towards home is substituted by four exit points located on major roads leading to the outskirts of the city. The North exit point is placed on Mansfield Road, which is the main transportation route for buses driving towards the northern part of the city. The South exit is located on London Road, which leads onto two main bridges across the river Trent. Nottingham has two major roads leading towards the western direction; Derby Road situated to the

[1] http://www.victoria-centre-nottingham.co.uk

northwest which in Canning Circus forks into Alfreton Road, Ilkeston Road and Derby Road, and Castle Boulevard constructed between the bottom of the Castle rock and Nottingham Canal situated on the southwestern part of the city centre. For the purposes of the simulation only one road (Derby Road) was selected from the provided options to represent the wester direction. Finally, the eastern exit point is placed on Daleside Road, which is the only main road leading towards the East.

As it was referenced by the interviewees, Old Market Square[2] was selected as one of the two open space areas. The square is a focal point of the city centre functioning as a popular meeting place. In addition, the square is also the area where local events, civic protests, royal visits, celebrations and public mourning take place. The open area between the Cornerhouse[3] and The Royal Centre [4] has been chosen as the second open space location for this use case. This area is situated on a crossroad of several main roads, therefore it serves as one of the transportation hubs for public transport out of the city centre. In addition, the pedestrianised open space in front of The Royal Centre which can hold a large number of people. Hence, it seems a likely place for assemble point. Approximate coordinates of the Nottingham case study preferred destinations are provided in Table 8.5 and the locations are also graphically displayed on a map in Appendix L.

Destination	Representation	Coordinates	
		Easting	Northing
Home	North direction: Mansfield Road (A60)	456951	341340
	South direction: London Road (A60)	458018	338362
	West direction: Derby Road (A6200)	455781	339789
	East direction: Daleside Road (A612)	458820	339134
Open space	Old Market Square	457106	339920
	The Cornerhouse and The Royal Centre	457134	340081
Incident	Victoria Shopping Centre	457382	340099

Table 8.5: Preferred destinations in Nottingham.

[2] http://www.nottinghamcity.gov.uk/oms
[3] http://www.cornerhouse.tv
[4] http://www.royalcentre-nottingham.co.uk

8.3.1.2 Leicester

In the Leicester case study the explosion is situated at one of the exits to the newly built Highcross Shopping Centre [5] oriented towards Causeway Lane. In comparison to Nottingham Leicester does not have a centrally located main square. The probably most known city landmark is the Haymarket Memorial Clock Tower which is also a popular meeting point. It is situated on a crossroad of five main roads through the city centre. This area has been recently pedestrianised. The road that runs eastwards from the Clock Tower is Humberstone Gate[6]. This wide street is sometimes used for major city events such as Christmas markets and fairs. Due to these reasons Humberstone Gate was selected as one of the two open space areas. Town Hall Square was chosen as the second open space location. This conservation area is the only significant green space which can be found in the centre of Leicester. It is also a site of public celebration and mourning. During sunny days this area also serves as a popular place for lunch hour breaks (Leicester City Council, 2005).

In Leicester two residential areas are located in the proximity of the city centre oriented towards the East and the West. The area on the East is bounded by the river Soar and the residential area on the West is delimited by the railway. The actual Leicester city centre is surrounded by a central ring road with exists oriented towards the outskirts more or less regularly distributed around it's perimeter. The four points representing routes towards home were selected from these roads. The northern exit is placed on St Margarets Way and the western direction is represented by King Richards Road. London Road, on which the main railway station is located, is selected as the eastern exit, and Welford Road depicts the exit towards South. Approximate coordinates of the preferred destinations are provided in Table 8.6. The locations are also depicted on a map in Appendix M.

[5] http://www.highcrossleicester.com
[6] http://www.crosbyheritage.co.uk/location/leicester/humberstone-gate

Destination	Representation	Coordinates	
		Easting	Northing
Home	North direction: St Margarets Way (A6)	458211	305656
	South direction: Welford Road (A5199)	459202	302594
	West direction: King Richards Road (A47)	457146	304274
	East direction: London Road (A6)	460438	302528
Open space	Humberstone Gate	459065	304663
	Town Hall Square	458843	304309
Incident	Highcross Shopping Centre	458498	304788

Table 8.6: Preferred destinations in Leicester.

8.4 Summary

This chapter began with definition of three model configurations which gradually incorporate the knowledge obtained by the experimental studies. This was followed by description of the key InSiM classes defining agent's behaviour. Subsequently, the model initialisation process and activities associated with one simulation step of an AWARE and UNAWARE agent were outlined in activity diagrams. The key behavioral algorithms were presented in a form of pseudo code. Finally, two case studies by which the InSiM implementation is tested were defined through assigning values of the key model parameters. The results of different simulation runs that are performed in order to compare the knowledge implemented in InSiM are reported in the subsequent chapter. The following chapter also includes analysis of the dispersion patterns that emerged from running InSiM with the defined use cases.

Chapter 9

Analysis of Results & Model Evaluation

9.1 Introduction

This chapter reports on the analysis of the data obtained by running InSiM on the defined use case scenarios. Twelve simulations were conducted to obtain data for all combinations of:

- model configurations (RAM, BEM, SAM),
- time periods under investigation (15 minutes, 30 minutes), and
- the locations of the explosion (Nottingham, Leicester).

Electronic Appendix II contains a short video capturing simulation of SAM configuration on Nottingham scenario. The aim of the analysis is to identify to what extent output of these simulations differ with respect to dispersion of agents on the simulation space at the end of the simulation time period. This is achieved by the application of analytical techniques that are capable of detecting differences between two agent distributions. The analysis provides evidence for evaluation of the hypotheses set-out in Section 9.2. The hypotheses are formed to identify whether additional behavioural and spatial considerations implemented into the agent's reasoning have an effect on its reaction. Based on the results, a conclusion is drawn as to whether incorporation of real-life information affects the simulation outcomes.

Analytical approach	Qualitative evaluation	Quantitative evaluation
Raster-based analysis	9.4.1: Visual Analysis of densities 9.4.2: Image Differencing	
Spatial statistics		9.5.2: Nearest neighbourhood function (on a network) 9.5.3: Nearest neighbourhood function (on a plane)
Conventional statistics		9.6.2: Goodness of fit test (distance from the incident) 9.6.3: Goodness of fit test (walked distance)

Table 9.1: Analytical techniques used for processing InSiM generated data.

The clustered nature of the data, caused by restricted movement of the agents on the road network, requires a careful approach to their analysis. Therefore, the data are assessed using several mutually independent approaches adopted from remote sensing (raster-based analysis), spatial, and conventional statistics. In addition, the data are analysed qualitatively and quantitatively (goodness-of-fit tests). This assessment enables the exploration of the data from various perspectives and allows a deeper insight than would be gained by use of a single analytical approach.

The techniques are summarised in Table 9.1 which also contains references to sections in which they are presented and discussed. This chapter concludes with evaluation of the InSiM functionality through validation, verification and calibration (Section 9.7).

9.2 Hypotheses

The following hypotheses, according to which the data were analysed, have been formed:

$H01_{15min}$: The dispersion pattern of agents generated by behaviour enriched by response reaction (BEM) does not differ from random movement (RAM) in the 15 minutes after the blast.

$H01_{30min}$: The dispersion pattern of agents generated by behaviour enriched by response reaction (BEM) does not differ from random movement (RAM) in the 30 minutes after the blast.

$H02_{15min}$: The dispersion pattern of agents which emerged from spatially aware behaviour (SAM) does not differ from the pattern generated by random movement (RAM) in the 15 minutes after the blast.

$H02_{30min}$: The dispersion pattern of agents which emerged from spatially aware behaviour (SAM) does not differ from the pattern generated by random movement (RAM) in the 30 minutes after the blast.

$H03_{15min}$: The dispersion pattern of agents which emerged from spatially aware behaviour (SAM) does not differ from the pattern generated by the behaviourally enriched response reaction (BEM) in the 15 minutes after the blast.

$H03_{30min}$: The dispersion pattern of agents emerged from spatially aware behaviour (SAM) does not differ from the pattern generated by the behaviourally enriched response reaction (BEM) in the 30 minutes after the blast.

The analytical techniques by which these hypotheses are evaluated were selected to provide the assessment at both the local and global level.

9.3 Constraints of the Data

The nature of the simulation results in the following constraints on the generated data. These constraints need to be considered during the analysis as they can affect its outcomes.

- **Homogeneity:** the points representing agents are not spatially homogeneous since they are naturally clustered towards the city centre (use of Gaussian distribution for placing the agents on the road network at the initialisation step of InSiM). Homogeneity in this instance means that a probability of a point being placed on a particular location is invariant regardless of the position of the location on the study region (Okabe and Okunuki, 2001).

- **Planar nature of the study region**: Although the road network is represented in 2D space by a pair of geographic coordinates of the nodes, the actual study area is constrained to a one dimensional graph. Therefore, the agents can only move along the graph edges. Hence, it cannot be assumed that the study area is planar.

- **Euclidean distance:** Due to the format of the simulation space the closest distance between two agents should be expressed as the shortest path between their locations on the network rather than an Euclidian distance as it is commonly expressed in a plane (Okabe and Okunuki, 2001).

9.4 Raster-based Analysis

The output of each simulation contains coordinates of all agents depicting their positions on the simulation space. This information can be transformed onto a map by representing location of each agent as a point on the road network. However, since an agent can share the same location with others, such representation does not provide any insight into how many agents are situated on the same place (especially at the destinations). Transforming the discrete point representation into a continuous surface allows us to gain additional information about the agents with respect to their densities.

Due to the natural clustering of the agents, the kernel density function was used to create the continuous surface resulting in a smooth distribution of values within the area (de Smith et al., 2007; Silverman, 1986).

The selection of the cell size of the raster by which the surface is represented does not affect its final appearance. However, the smoothness of the surface is highly influenced by the extent of the kernel search radius as well as the type of kernel function used (de Smith et al., 2007, pg. 131). ArcView, which performed the analysis, only uses a quadratic function to define the shape of the kernel. Therefore, it was not possible to assess the impact of different kernel shapes on the final density surface. However, a number of tests were conducted to define the most appropriate search radius.

The tests were made with distances starting at 10 m (narrowest street considered in definition of the walkway width categories rounded to the closest factor of ten; Table 7.3) gradually growing up to 30 m (the widest street). However, the produced surfaces (especially those representing the situation in 30 minutes after the blast) still remained very "bulky". After a number of additional tests the final search radius was set to 50 m. This extent was selected as a compromise where the bulkiness was not as prominent yet the densities remained clustered around the road network. The size of the density raster cell was setup to 10 m to approximately represent the width of the narrowest street.

The Geometrical Interval classification method (Frye, 2006) was developed to organise data that are not distributed normally (road network constraint) or are skewed by a preponderance of duplicate values (large clusters at the preferred destinations), and hence is the most appropriate approach to visualise the generated surfaces. To more closely inspect patterns with lower density values, ten categories were selected for the classification. The extent of the categories must remain the same for all twelve generated surfaces to enable their comparison. The final definition of the categories was selected with respect to the results of classification conducted on the density surface with highest range of the kernel function values.

Since the majority of the raster cells hold a zero value (areas outside the road network), application of any formal statistical tests for evaluation of the null hypotheses would not provide any satisfactory results. In addition, the differences for densities on the preferred destinations are an order of magnitude different from those depicted on the road network. This might also affect the outcomes of the statistical test. For these reasons, the density surfaces were compared qualitatively, i.e. by visual inspection of the differences.

9.4.1 Visual Analysis

According to Lu et al. (2004) the visual analysis approach to identification of differences between two rasters can reveal patterns which would not be discovered by quantitative analysis. As distinct from an automated algorithm, human experts can evaluate the differences qualitatively with use of experience, knowledge, and common sense. Therefore, small scale patterns or patterns which would be evaluated as insignificant may be detected. These small scale patterns may reveal important information about the studied phenomenon (Lu et al., 2004).

Hence, visual analysis of the differences is a logical first step of the results evaluation process. As this is a qualitative approach, it is not possible to measure the extent of the differences. Quantitative differences are evaluated by the alternative approaches discussed in the following sections.

9.4.1.1 Results

Figures 9.1 and 9.3 provide 2D view of the density surfaces generated for all three model configurations of both the Nottingham and Leicester use cases for two time intervals of interest (15 minutes and 30 minutes). To gain an addi-

Model Configuration	Nottingham use case	Leicester use case
RAM_{15min}	a)	a)
BEM_{15min}	b)	b)
SAM_{15min}	c)	c)
RAM_{30min}	d)	d)
BEM_{30min}	e)	e)
SAM_{30min}	f)	f)

Table 9.2: Key to Figures 9.1 - 9.4.

tional view of the data, 3D visualisation of the same surfaces are presented in Figures 9.2 and 9.4. A key to the organisation of the images within the figures is provided in Table 9.2 and values of the colour-coded density categories in Figure 9.5.

In the following sections the results are discussed with respect to the defined hypotheses. The results of the analysis demonstrate similar dispersion patterns in both cities. In addition, similar trends can be detected in the density surfaces representing the situation for 15 and 30 minutes after the explosion. Therefore, the hypotheses proposed for exploration of differences between the same configurations (e.g. $H01_{15min}$ and $H01_{30min}$) are evaluated together and discussed simultaneously.

9.4.1.2 Evaluating hypotheses $H01_{15min}$ and $H01_{30min}$

Visual comparison of images a) and b) (Figures 9.1, 9.2 for Nottingham and Figures 9.3, 9.4 for Leicester) indicates a difference between the two dispersion patterns. While surfaces representing RAM densities show agents homogenously distributed around the city centre, the representation of BEM configuration indicates several trends:

- Higher densities are observed along the roads leading towards the outskirts of the city. This is a consequence of agents moving towards *home*. In the images representing the 30 minutes scenarios this trend has shifted nearer the four exit points since agents had more time to move closer to the outskirts of the cities.

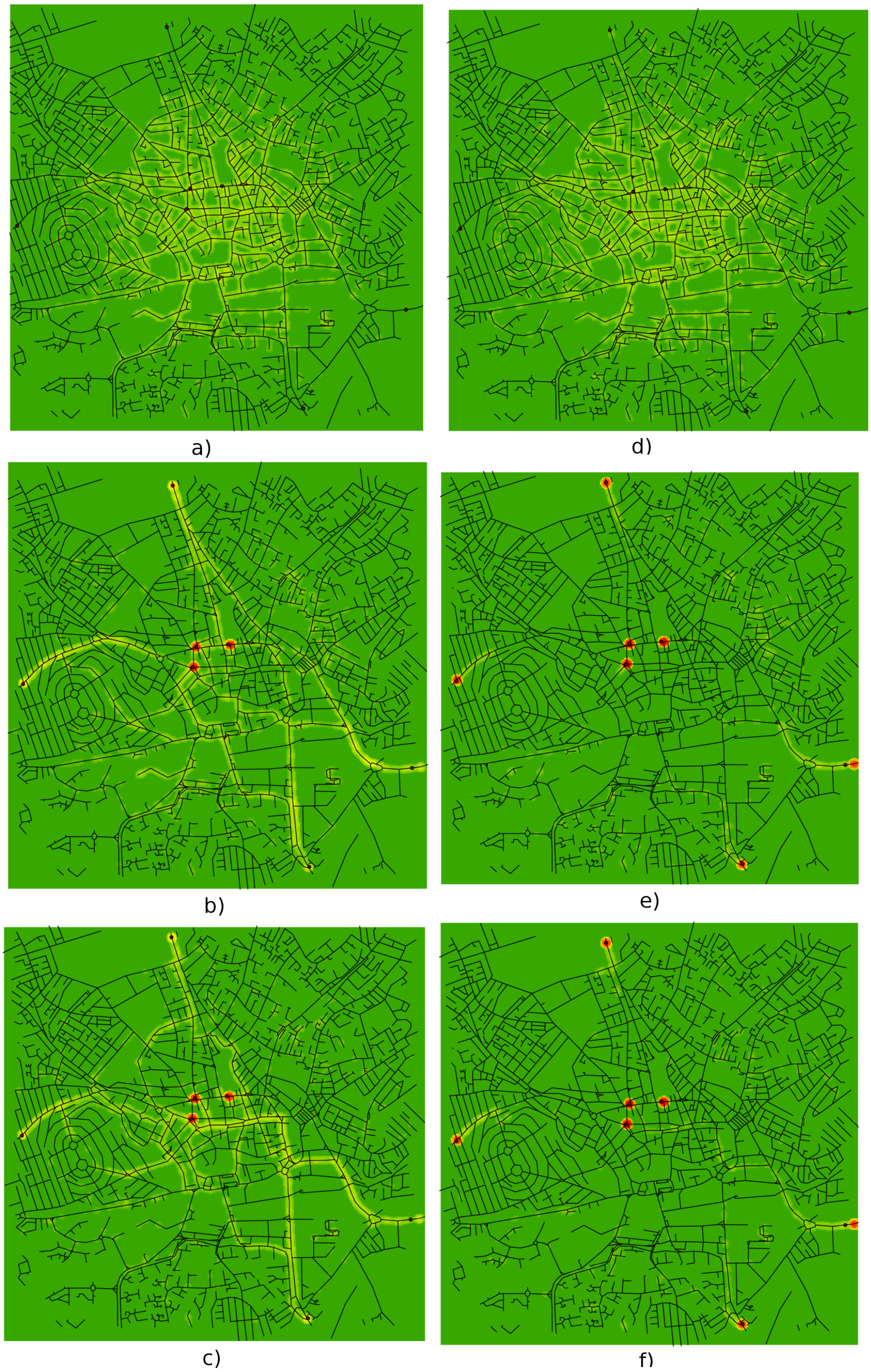

Figure 9.1: Density of agents in Nottingham use case.

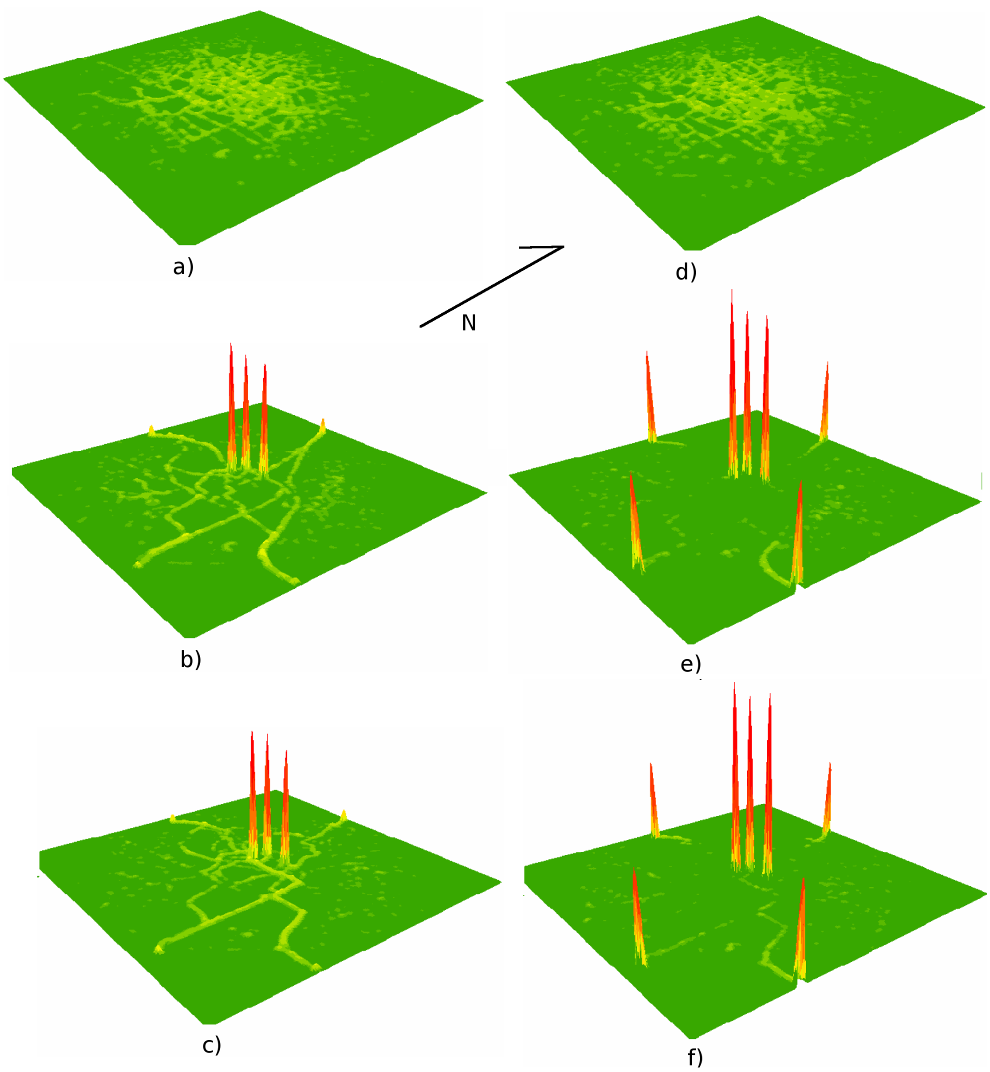

Figure 9.2: 3D visualisation of Nottingham use case densities.

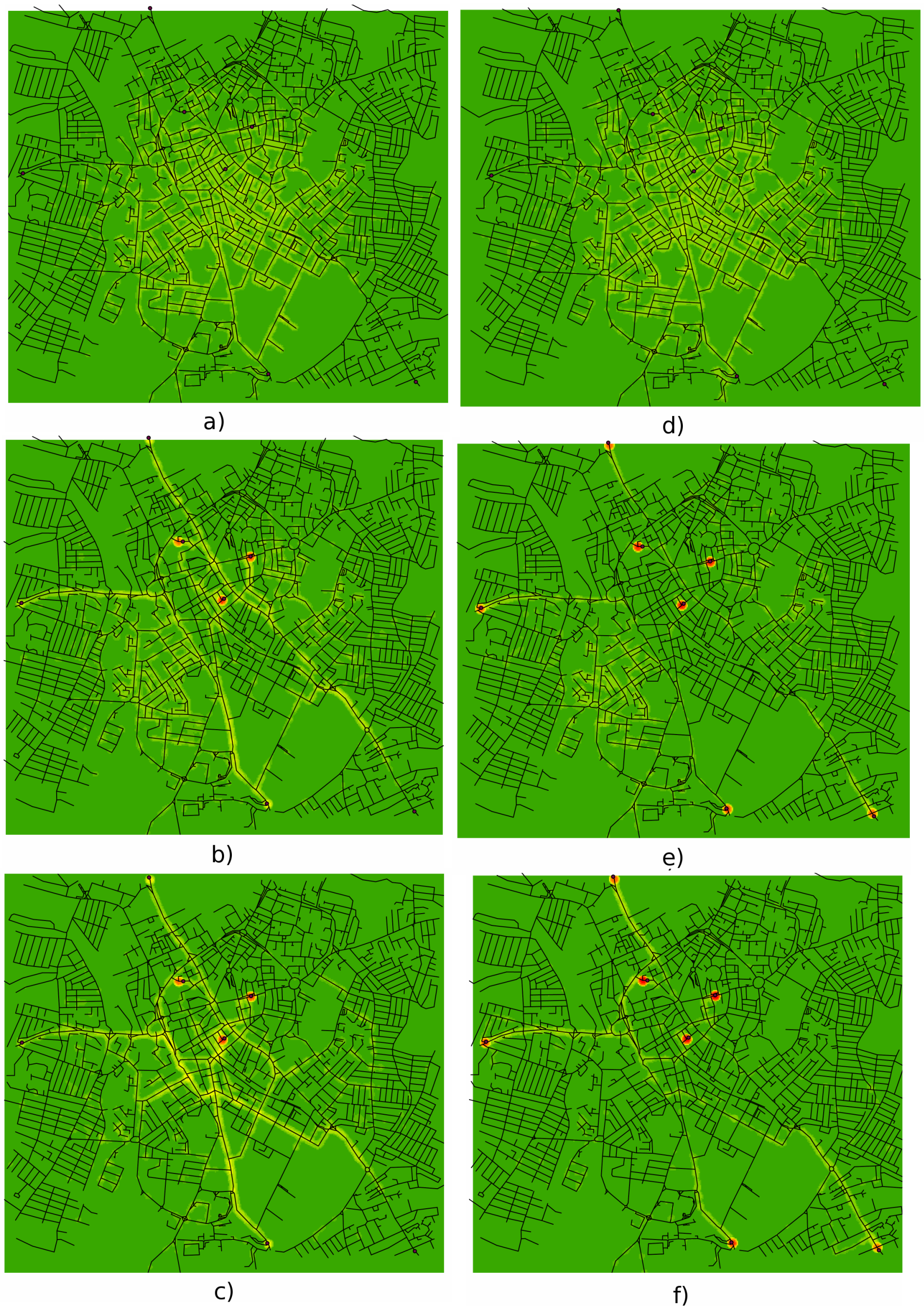

Figure 9.3: Density of agents in Leicester use case.

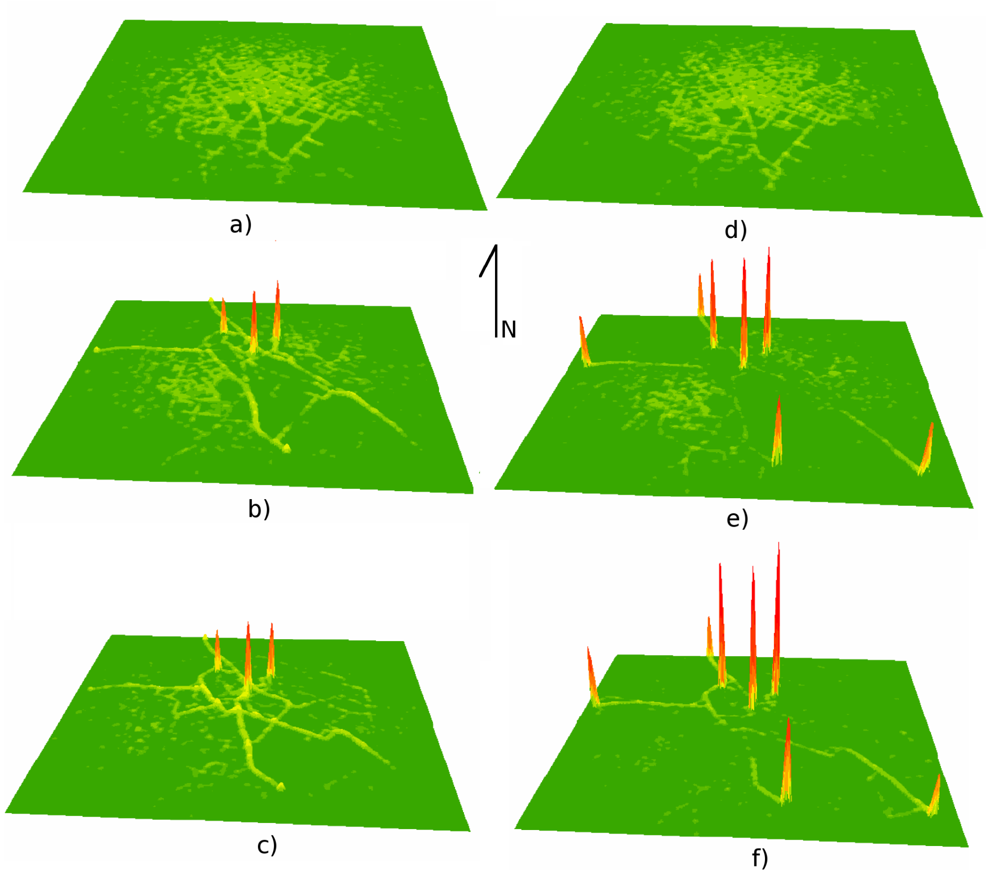

Figure 9.4: 3D visualisation of Leicester use case densities.

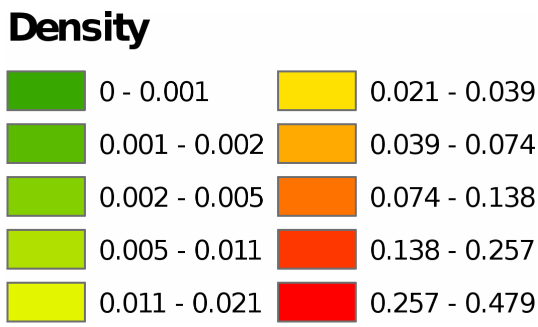

Figure 9.5: Distribution of the density categories.

- Three high density spikes, apparent in images b), indicate that a large number of agents have already reached the *open areas* and the *incident* in 15 minutes after the explosion. Since the exit points are located further away from the incident, no spikes can be observed at the *home* destinations in the 15 minutes period. Nevertheless, the high density clusters at these destinations are prominent in the surfaces representing the situation in 30 minutes after the explosion (image e) indicating that even these remote destinations can be reached in half an hour time.

9.4.1.3 Evaluating hypotheses $H02_{15min}$ and $H02_{30min}$

Differences can be observed by comparing images a) and c) representing densities of RAM and SAM configurations in 15 minutes after the blast, and d) and f) depicting the distribution of the agents in 30 minutes. The areas of the largest differences are:

- the locations depicting preferred destinations (high density spikes), and
- the roads leading towards the four city exit points (creating clusters on the most favourable routes).

This reflects the difference in the agent's behaviour. While in RAM configuration the agents are walking towards different areas, the SAM agents are congregating towards seven specific locations forming density clusters at the destinations and along the way.

9.4.1.4 Evaluating hypotheses $H03_{15min}$ and $H03_{30min}$

The differences in dispersion patterns between BEM and SAM configurations are not as apparent as those observed by comparison with RAM model. Closer inspection of the images b), c) and e), f) in 2D and 3D view reveal local differences in the:

- Nottingham:
  - densities covering the area situated SE of the incident, and
  - densities in the SW and NE map quadrants;
- Leicester:
  - agent densities situated in the SW and SE map quadrants,
  - densities in the area around the *open space* destination located on Humberstone Gate,
  - height of the density spikes on the centrally located destinations 30 minutes after the explosion.

The differences are a consequence of uneven navigational preferences of BEM and SAM agents. Since 62 % of SAM agents that are aware of the explosion walk on the wide walkways, the densities in images c) and f) are more clustered towards main roads. Due to the different street layout this pattern is more prominent in Leicester. Since the area in the SW quadrant of the Leicester map is predominantly formed from narrow local streets, it has, in SAM configuration, been avoided by agents prioritising wider walkways. Similarly, an apparent cluster can be observed on a main road leading towards the Leicester's East exit point in images c).

The SAM agents reach the central destinations sooner than BEM agents since the route becomes shorter than the actual geometrical distance, due to the weight by which the preferred walkways are multiplied. This causes the height difference of the three centrally located density spikes between images e) and f).

9.4.1.5 Assessing Applicability of the Technique

The main advantage of the visual comparison is that apparent differences between any two configurations can be immediately detected. The density maps with equal distribution of the density categories are very intuitive and easy to read. The 3D visualisation of the same data enables us to observe the situation from a different perspective providing an additional insight into the analysis. However, this approach has also several shortcomings. Although it provides a good means for detecting high level trends and patterns, identification of local or small scale differences is more difficult. Moreover, the hypotheses are assessed based on subjective opinion of the researcher without introducing a single objective measure by which the significance of the detected changes can be determined.

9.4.2 Image Differencing

This approach is inspired by change detection techniques widely applied in the processing of remotely sensed data. In this research it is applied to eliminate some of the shortcomings of the preceding analysis. Change detection is usually used for identification of temporal changes (e.g. monitoring changes in tropical forest Singh, 1986 or in land-cover Sohl, 1999). However, in this instance, the change under investigation is related to effects caused by two different model configurations. As in the previous analysis, the dispersion patterns of the agents are represented by density rasters of the same cell sizes and extents.

According to Lu et al. (2004) the most straightforward technique of change detection is image differencing. Image differencing involves subtracting the value of each cell in one raster from the value of the same cell in the second raster (Jensen, 1986). For the analysis *Raster Minus* function implemented in Raster Math Toolset of the 3D Analyst Toolbox in ArcMap is used to generate the desired rasters.

9.4.2.1 Limitations

A critical element of this technique is to define the threshold based on which the calculated change can be classified as significant (Jensen, 1986). This threshold is usually set with respect to the nature of the data and the purpose of the analysis (Lu et al., 2004). Since it is not possible to set the threshold in the Raster Math Toolset, the evaluation of the significance of the detected change needs to be done after the resulting raster is generated.

The change is expected in both directions i.e, the density value in the first raster can be larger or smaller than the density value in the second one. Therefore, to avoid negative values, the generated raster is transformed into absolute values.

The assessment of the significance of the changes requires a careful approach due to the natural clustering in the data. The following issues need to be considered before the assessment approach is selected:

- The majority of the raster cells hold zero value (locations outside the road network). These cells will in the resulting raster remain unchanged. The assessment method needs to exclude these cells from evaluation of the changes since they are not connected with the phenomenon under investigation.
- The visual analysis presented in the previous section detected high density values at the locations of preferred destinations. It is expected that the value of the image differencing on these locations will be higher than in other areas. Therefore, using the same threshold value across the whole area would result in loosing some of the phenomenon specific information if the classification of the resulting raster is strictly kept to change/no change values.

Due to these issues, application of statistical tests to measure the extent of the differences (e.g. Kolmogorov-Smirnov test, or Quadrant counts as used in Egh-

Hypothesis	Nottingham use case	Leicester use case
$H01_{15min}$	a)	a)
$H02_{15min}$	b)	b)
$H03_{15min}$	c)	c)
$H01_{30min}$	d)	d)
$H02_{30min}$	e)	e)
$H03_{30min}$	f)	f)

Table 9.3: Key to Figures 9.6 - 9.9.

bali, 1979 and Diggle, 2003) would not be appropriate. Moreover, the extensive amount of extreme value cells would significantly bias the calculation. Therefore, qualitative approach, reporting the changes based on visual observation of the resulting raster, was selected. This approach also enables observation of the changes at both, local and global level. Although the extent of the difference cannot be measured in any formal way, the analysis can reveal patterns that have not been detected by the visual comparison reported in Section 9.4.1.

9.4.2.2 Results

The results of the image differencing for Nottingham use case are displayed in Figure 9.6 and for Leicester in Figure 9.8. Since 3D visualisation used in the previous approach revealed additional information not apparent in the 2D view the changes are also represented in 3D (Figures 9.7 and 9.9). Table 9.3 provides a key to organisation of the images in the figures.

The classification of the density categories remains the same as in the previous approach (Figure 9.5). However, in this case, the categories represent differences in densities rather than their actual values.

9.4.2.3 Evaluation of the Hypotheses

Visual observation of the density surfaces representing information with respect to the $H01_{15min,30min}$ and $H02_{15min,30min}$ hypotheses support the findings identified by the previous approach. Raster differencing provided additional insight into the evaluation of hypotheses $H03_{15min,30min}$ as small scale changes

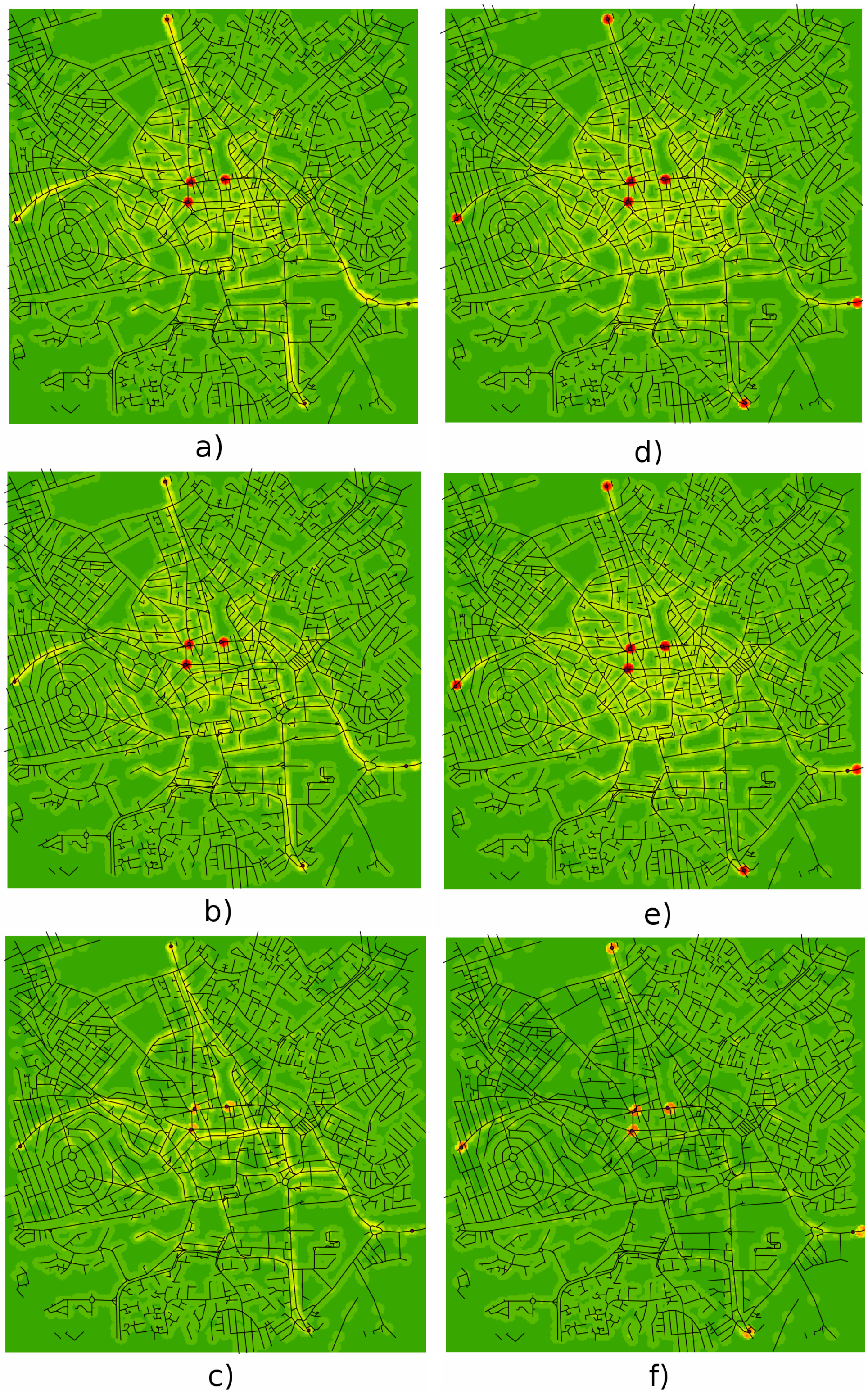

Figure 9.6: Raster differencing of agent densities in Nottingham use case.

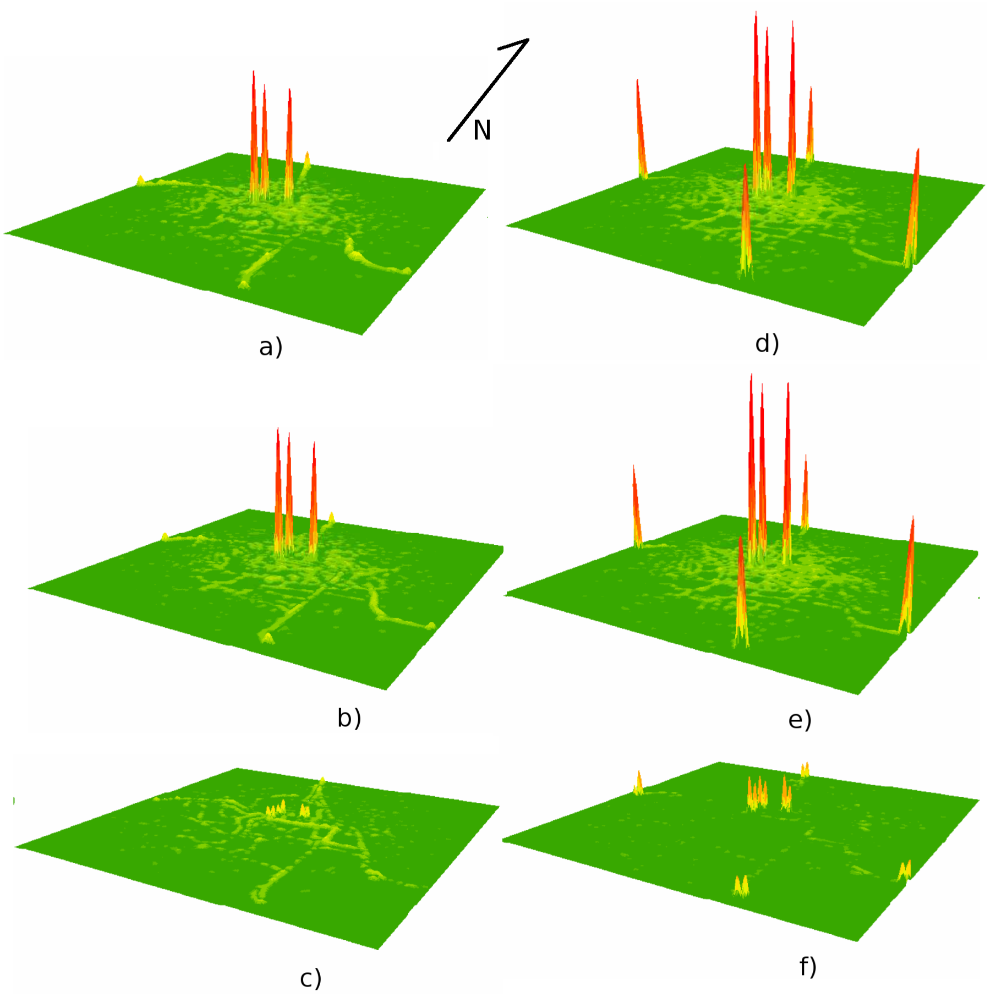

Figure 9.7: 3D visualisation of raster differencing in Nottingham use case.

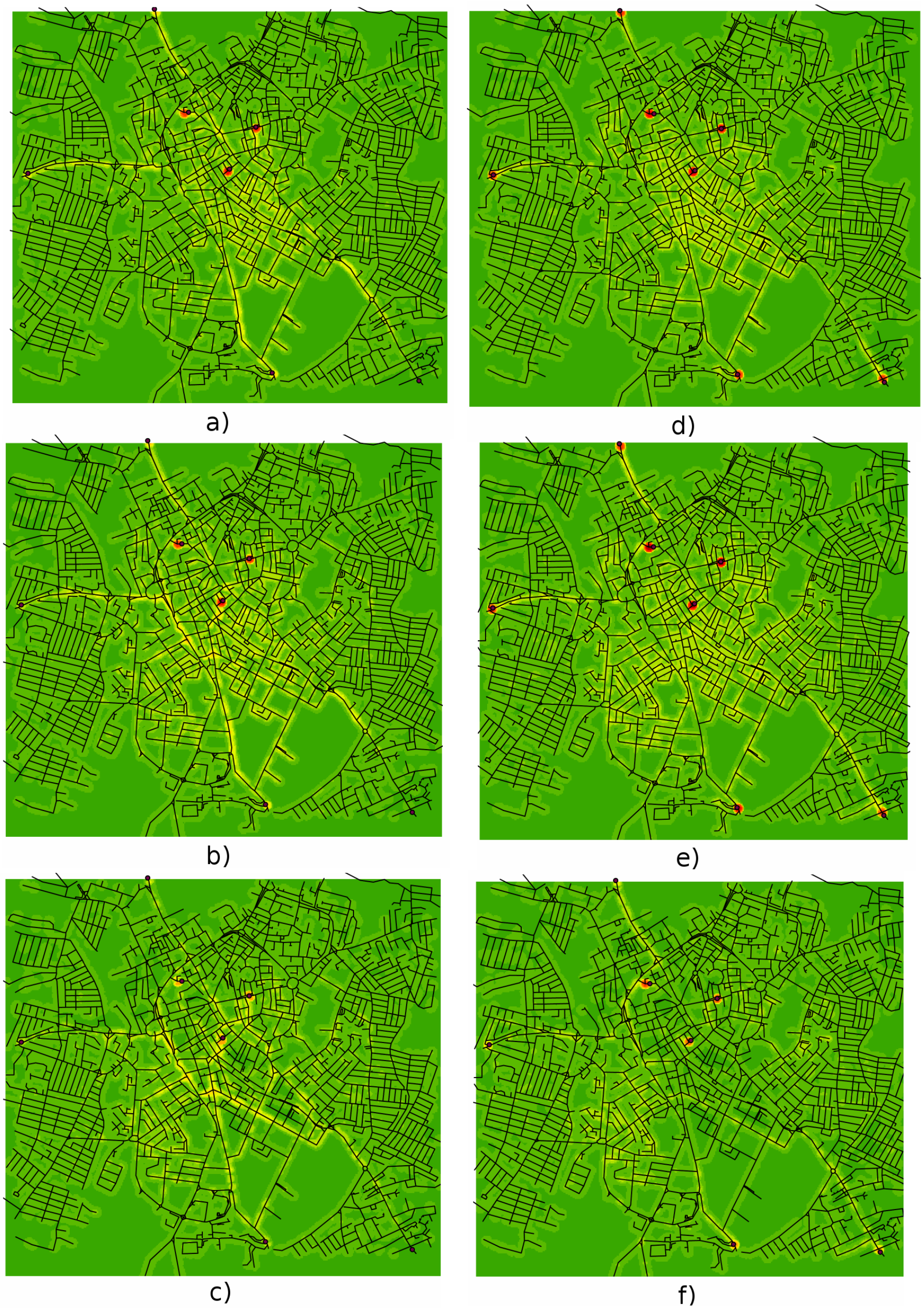

Figure 9.8: Raster differencing of agent densities in Leicester use case.

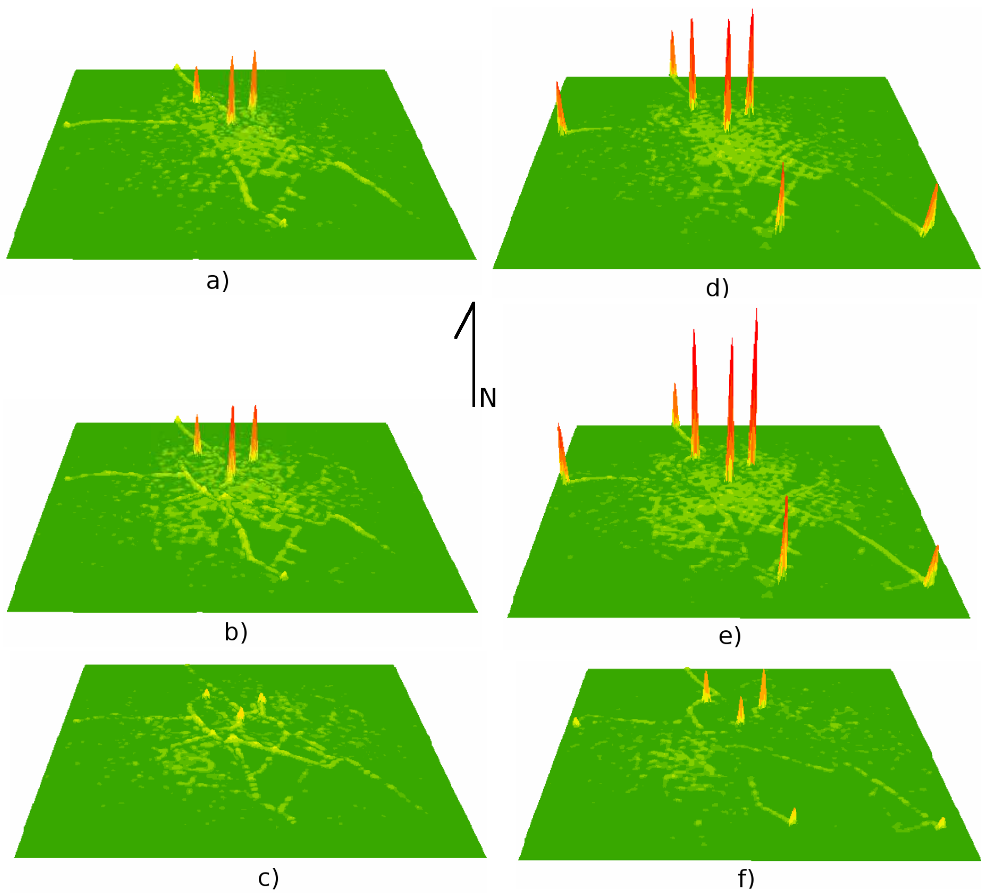

Figure 9.9: 3D visualisation of raster differencing in Leicester use case.

which were not previously identified were depicted. These are:

- The density spikes at the preferred destinations demonstrate the differences in number of agents that have already reached their target.
- The different navigational preferences of BEM and SAM agents caused the higher density values on wide and narrow walkways. These values indicate the areas where the difference in navigation is most apparent. Due to the different layout of streets in Leicester, these changes are more visible in Figures 9.8 and 9.9.

9.5 Spatial Statistics

In this research, the term spatial statistics refers to techniques that look for evidence of spatial independence at local level, i.e. between a pair of agents coming from two different simulation configurations. These techniques are referenced by Diggle (2003) as point pattern analysis. The coordinates depicting final locations of agents generated by different InSiM configurations form the three point patterns for which the spatial statistics are calculated. In contrast to the raster analysis reported in Section 9.4, spatial statistics enable quantitative assessment of the changes, i.e. determining whether the extent of the differences is statistically significant.

In order to evaluate the hypotheses the two point patterns representing agents from different InSiM configurations are merged into a single bivariate point pattern (BPP). The small-scale relationships between the two agent distributions can be detected by assessment of the nearest neighbourhood distances from the *i*th point in pattern A to the nearest *j*th point from pattern B against which A is compared (Equation 9.5.1; Diggle, 2003).

$$\hat{G}_{ij}(d) = \frac{\sum_i 1\{t_{ij} \leq d\}}{n_i} \tag{9.5.1}$$

The argument n_i depicts number of points in A, the argument t_{ij} represents the distance from point i in A to the nearest point j of B, d represents the values at which the $\hat{G}_{ij}(d)$ function is estimated.

The detection of possible aggregations is done by evaluating the measured (empirical) nearest distances ($\hat{G}_{ij}(d)$) with an estimate of cumulative distribution function $G_{ij}(d)$ (Equation 9.5.2) which represents the relations of independent point patterns under complete spatial randomness (CSR) which are Poisson distributed around the study area (Diggle, 2003).

$$G_{ij}(d) = 1 - e^{\lambda_j \pi d^2} \tag{9.5.2}$$

The argument λ_j depicts the intensity of B (Diggle, 2003). Deviations between the empirical and theoretical curves may suggest dependence between the points of the two patterns. However, this comparison does not indicate how significant the difference is. Therefore, in order to determine statistical significance of the difference, a test of goodness-of-fit needs to be conducted (Diggle, 2003; Okabe et al., 1995). This can be done by computing analytically the theoretical function and plotting its extreme values, or by applying the Monte Carlo simulation approach (Atkinson et al., 2007).

The null hypothesis of the goodness-of-fit tests reads:

> Points in pattern B are randomly and independently distributed in relation to the points in pattern A.

The outcomes of the goodness-of-fit hypothesis testing provide information based on which the hypotheses presented in Section 9.2 can be evaluated. Further explanation of the goodness-of-fit test is provided in the following paragraphs.

9.5.1 Approach Limitations

The application of the G-function in its original state is limited by the following assumptions:

- The BPP is stationary (spatially homogeneous).
- The BPP represents a process in the plane.
- The two point patterns are independent on each other (Diggle, 2003; Baddeley and Turner, 2008).

The nature of the evaluated BPPs fulfill only the assumption of independence since the locations of agents in one point pattern are not dependent on the locations of agents in another point pattern. The remaining assumptions are not met due to the clustered nature of the data. Therefore, the results of the statistical tests require careful assessment since they could be biased due to the violation of the above assumptions.

To limit the biases it is desirable to adapt the calculation of the theoretical G_{ij} function to acknowledge the strong natural clustering of the BPP on the road network. The following two sections demonstrate examples of how this was done.

9.5.2 Network-based Analysis

The planar space was replaced by a network. Subsequently, all calculations were conducted with respect to the one dimensional space. This approach was adopted by Okabe and Okunuki (2001) who have developed a GIS-based toolbox SANET (Spatial Analysis on a NETwork; Okabe et al., 2006). This toolbox focuses on analysing point patterns in network environments embedded on a plane.

SANET was not, at the time of this research, freely available for download. However, after an email discussion with the developers, the use of SANET for the purposes of this research project was permitted. In the provided version (V 3.3), SANET was developed as an extension of ArcMap. This meant that the road network generated for the purposes of InSiM could be reused without any further processing.

Due to the complexity of the road network, the network analysis could not be done over the whole study area. SANET can only manage calculations of up to 7,000 polylines (SANET, 2009). The road network could be further simplified, however, this would not have significant effect on the final number of edges since in SANET all the points of the BPP are transformed as additional nodes of the graph dividing each exiting edge into two. This means that the calculations could only be done with a significantly smaller number of agents in each point pattern. This would, however, not provide any relevant information for evaluation of the stated hypotheses since the obtained results would not be representative of the whole study area. Nevertheless, due to its high relevancy with this research project, it was decided to experiment with SANET on a small region to test its functionality.

9.5.2.1 Estimation of Nearest Neighbourhood Distance with SANET

In accordance with the planar spatial statistics, SANET uses a Poisson distribution for calculation of the values of the theoretical G-function. However, in this case the distribution is related to a network rather than a plane. Detailed explanation of how the values are calculated can be seen is Okabe et al. (1995).

A small centrally located sub-region was selected from the Leicester use case (Figure 9.10 a)) to undertake the test. The region contains 210 edges and 163 nodes (Figure 9.10 b)). In Figure 9.10 c) the point pattern displayed in red (49 points) depicts locations of agents generated by BEM at 15 minutes after the

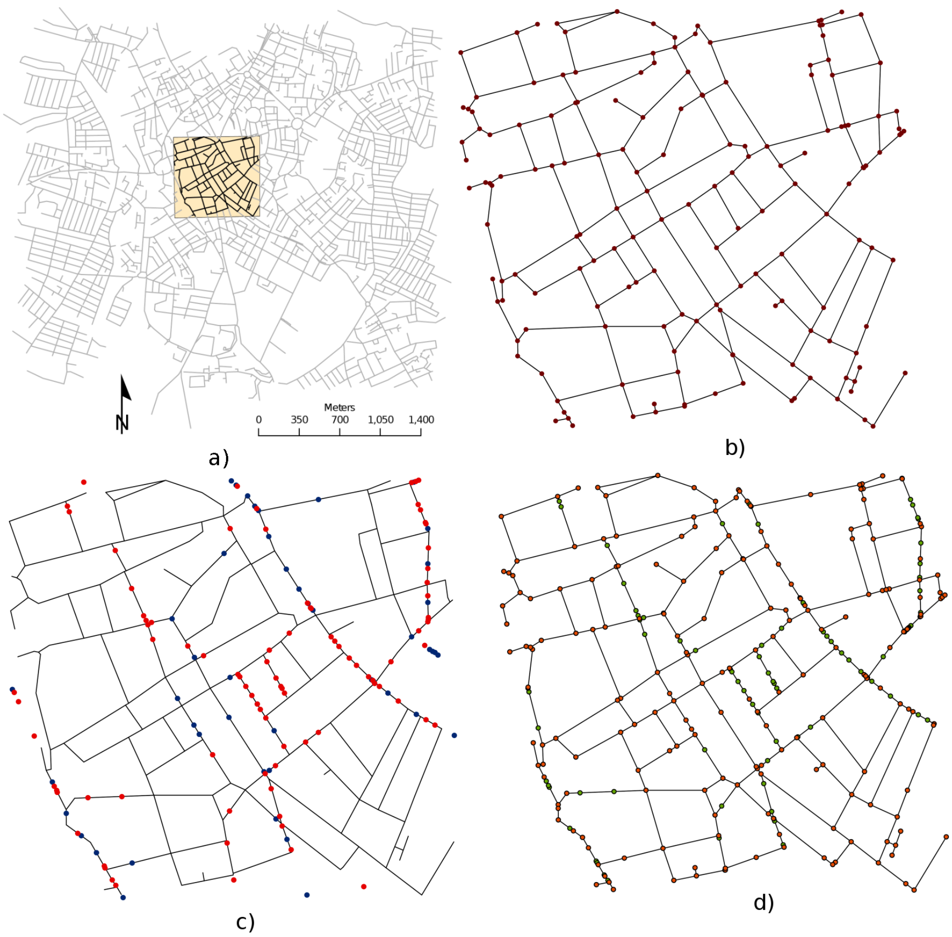

Figure 9.10: Test region for SANET.

blast, blue points represent the same situation but generated by SAM configuration (92 points). The filtering of edges at the border of the region caused several points to "float" in space. These were assigned to the nearest edge of the existing network during the *Insert points to a network* operation used in SANET to associate the point patterns with the network. The final road network after both point patterns were added as nodes consisted of 336 edges and 289 nodes (Figure 9.10 d)).

The goodness-of-fit test was conducted with *Conditional nearest neighbour distance method* function. The settings of the interval of frequency distribution table (*all*) and the distance measurement method (*by link length*) were kept as default since the relations are going to be evaluated at the whole range of the nearest distances derived from the Poisson distribution (from minimum to the maximum). The results are displayed in Figure 9.11 where the cumulative empirically measured distances (cumulative observed curve) are compared to values of the cumulative theoretical function. The extreme 5 % of the cases (the number of points at the upper and lower 5% of the theoretical function) are included to be able to assess the significance of the differences.

Since the empirical distances (cumulative observed curve) are laying outside of the interval delimited by the 5 % upper and lower curves, the relationship between the two point patterns is stronger than random. The curve indicates clustering since it progresses quicker than the theoretical distribution. The graph also indicates that 5 BEM points are located at the same places at SAM points (distance is 0 metres). The steep shape of the empirical function at the shorter distances denotes stronger clustering up to approximately 20 meters.

Based on this results the null hypothesis cannot be, for the selected region, supported. This indicates that the BEM agents tend to be located in the proximity of SAM agents. It can be concluded that the additional knowledge implemented in the SAM configuration does not provide significantly different distribution of agents from outcomes of the BEM configuration. However, this finding cannot be generalised for the whole study area.

9.5.3 Analysis on a Plane

The second approach to limit the biases caused by the clustered nature of the data was to adjust the shape of the study region to limit the area on which the theoretical distribution of the bivariate pattern is generated. This means that although the calculations remain planar they are more focused to a *window* which closely embraces the road network.

The *window* was created by converting the road network into a raster with val-

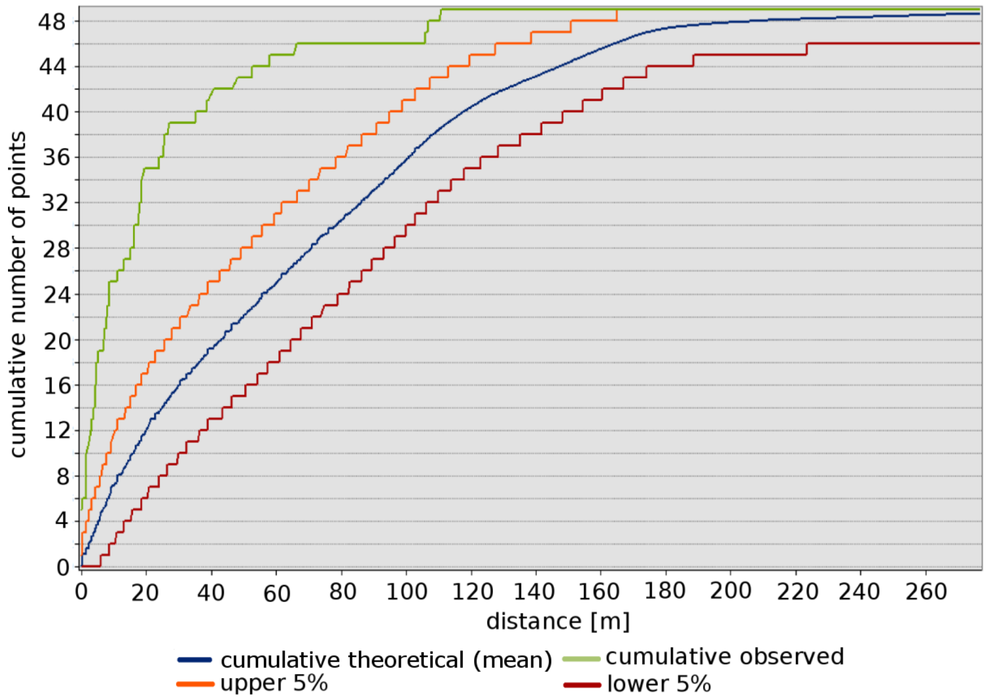

Figure 9.11: Estimates and observed values of G-function in the test region.

ues 1 and 0, where 1 refers to areas included in the *window* and 0 to area excluded from the planar space. After experimentation with different cell sizes the final *window* was defined by a cell size of 20 m x 20 m (Figure 9.12). However, due to this transformation several problems occurred:

- Actual topological relations between connected roads were broken or new false ones were added (see a closeup in Figure 9.12) resulting in some cases in miscalculation of the closest distance.

- The window is of a very complex shape containing large number of holes (white space) making the calculation computationally very expensive (not possible to run on a standard PC: dual core processor 1.6GHz, 2GB of RAM).

- The calculation of the shortest distance is not as precise as on the network.

For the evaluation of the nearest neighbourhood distances on a plane SPATSTAT package (Baddeley and Turner, 2008) of *R* (open sources environment of statistical computing; R project, 2009) has been used. As with SANET, the ap-

Figure 9.12: Rasterisation of the road network in Leicester use case.

plicability of SPATSTAT was tested to identify whether it can be used as a valid approach for evaluation of the stated hypotheses.

9.5.3.1 Estimation of Nearest Neighbourhood Distance with SPATSTAT

In contrast to SANET, which uses analytical function to undertake the test of goodness-of-fit, SPATSTAT uses a Monte Carlo simulation approach to obtain the expected values. This means that instead of evaluating the empirical function against a single theoretical function, it is compared with a simulation estimate of its theoretical distribution functions under complete spatial randomness (CSR). Each of the simulated BPP represents a Poisson distribution with the same intensities as the empirical dataset (Baddeley, 2008).

The simulation estimate for $G_{ij}(d)$ is hence calculated as a mean of all the estimated simulation functions ($\hat{G}_z(d), z = 1, ..., m$) as depicted in Equation 9.5.3, where m represents the number of independent simulations under CSR in the given region with the same number of points as the empirical distribution.

$$\bar{G}_{ij}(d) = \frac{\sum \hat{G}_z(d)}{m} \tag{9.5.3}$$

The significance of deviation between the simulated CSR distribution $\bar{G}_{ij}(d)$ and the empirical distribution $\hat{G}_{ij}(d)$ can be assessed against the upper and lower simulation envelopes denoting the maximum and minimum values of the estimated simulation functions (Equations 9.5.4 and 9.5.5).

$$U(d) = \max_{z=1,...,m} \hat{G}_z(d) \tag{9.5.4}$$

$$L(d) = \min_{z=1,...,m} \hat{G}_z(d) \tag{9.5.5}$$

The null hypothesis of independence between the two point patterns can be evaluated by plotting the $\hat{G}_{ij}(d)$ against the envelopes U(d) and L(d). The significance level of the Monte Carlo test can be calculated as $\alpha = 2/(M + 1)$, where M represents number of the estimated simulation functions ($\hat{G}_i(d)$; Diggle, 2003). Hence, in order to evaluate the relationship with 95 % probability 39 estimated simulation functions must be generated (z = 39).

In the calculations problems caused by edge effects must be considered. As Diggle (2003) argues, the distances measured at the border of the study region are highly biased because they are denied the possibility to have neighbours outside. Hence, to minimise the influence of the edge effect a correction should be employed. However, in this analysis no edge effect correction was applied since the people located outside the city (out of the simulation environment) do not have any influence on the behaviour of the agents located in the central area of the city.

This approach has a number of constraints which limit its application:

- The stochastic approach used for generation of the estimated simulation functions ($\hat{G}_z(d)$) does not directly denote the relationship between the two point patterns, but rather between the BPP and a randomly created BPP. Therefore, the results of the goodness-of-fit test can only indicate whether the two point patterns are distributed randomly with respect to each other. This does not take into consideration the natural clustering in the data.
- The intensities used for calculation of the theoretical function (Equation 9.5.2) creates additional problems with respect to information loss due to the discretisation of the continuous space into the raster cells.

To identify the extent of influence of the limitations on the test statistics, the approach was tested on a comparison of BEM and SAM configurations for the Leicester use case depicting the situation 15 minutes after the blast. The results are displayed in Figure 9.13.

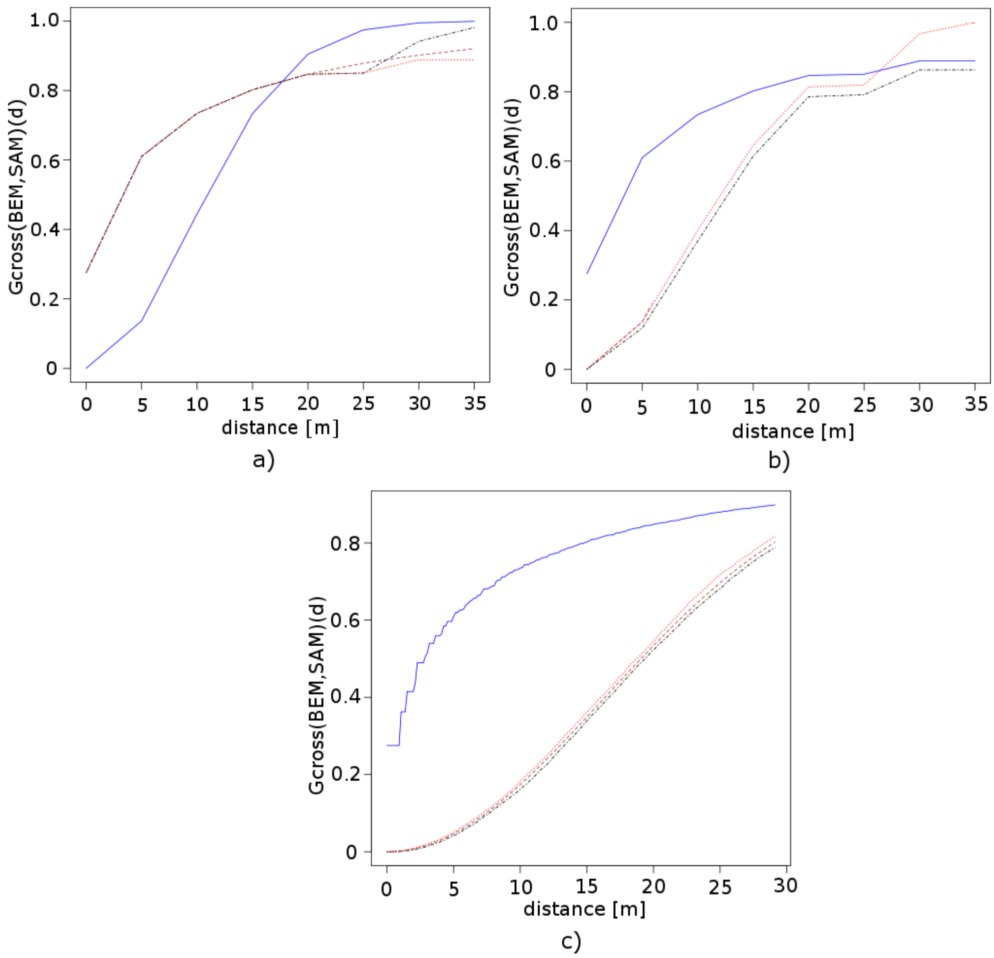

Figure 9.13: Results of the G-function evaluation in a plane.

In image a) the blue line represents the theoretical function G_{ij} calculated by Equation 9.5.2. The brown dashed line depicts the empirical function $\bar{G}_{ij}(d)$ without application of edge effect correction. The red dotted line represents application of Kaplan-Meier method of $\bar{G}_{ij}(d)$ and the black dot-and-dashed line illustrates application of "reduced sample" estimator for edge effect correction (see Baddeley, 2008, for additional information regarding the edge effect correction). Since the $\bar{G}_{ij}(d)$ progresses differently than G_{ij} it can be concluded that the relationship between the two point patterns is not random. It also indicates that for up to 20 m there is no difference between the uncorrected function and the functions corrected of an edge effect. This means, that the edge effect does not have a strong influence on the short distances.

Image b) depicts results of application of goodness-of-fit test ($z = 39$). The upper and lower envelopes are represented by the red dotted line and black dot-and-dashed line respectively. The $\bar{G}_{ij}(d)$ function (blue) progresses faster (up to 25 m) than the simulation envelopes. This is a sign of clustering between the two point patterns. After the 25 meter distance, the function progresses within the bands delimited by the upper and lower envelopes. This means, that in the longer distances the two point patterns are independent on each other. The natural clustering in the data is most apparent at the distance d = 0 m. This shows that 30 % of agents are located in the same positions reflecting the high density spikes on the preferred destinations identified by the preceding analytical techniques.

Finally, image c) illustrates the results of the goodness-of-fit test which is conducted on 2D plane without any restriction put on the representation of the road network by the *window*. The red and black curves depict the simulation envelopes, brown dashed line indicates the theoretical function G_{ij} and the empirical function ($\bar{G}_{ij}(d)$) is represented in blue. In this instance, the test revealed strong clustering between the BPP since $\bar{G}_{ij}(d)$ progresses significantly higher than the simulated envelopes. This test clearly indicates that use of the *window* reduced some of the biases caused by problems due to the natural clustering in the data.

9.5.3.2 Evaluation of the Hypotheses

In the previous section it was highlighted that the transformation of the road network into the planar *window* causes loss of information. This affects the results of the test statistics since the values of both the theoretical function G_{ij} and the empirical function ($\bar{G}_{ij}(d)$) are calculated as the shortest Euclidean distance on the plane. Hence, it is inappropriate to apply this analytical approach for evaluation of the presented hypotheses.

The results of the statistical tests would provide false outcomes reflecting the clustered nature of the data rather than the existing relationship between two point patterns. Further investigation into this matter needs to be conducted to determine the extent of the influence of the simulation space on the results of the statistical tests.

9.6 Conventional Statistics

To gain an alternative perspective on the data the spatial information is converted into a vector representing a single aspatial variable. Consequently, the values of the variable from two independent datasets are tested with the use of conventional statistical goodness-of-fit tests. Similar to raster-based analysis and spatial statistics the aim of the conventional statistics is to identify whether any two InSiM configurations denote significantly similar dispersion patterns of agents (reflecting the set of hypotheses presented in Section 9.2).

The approach adapted in this analysis is based on the concept of *distance*. The spatial information depicting locations of the agents is transformed into a single variable representing:

- an Euclidian distance between each agent and the incident (Section 9.6.2);
- the length of the path each agent walked during the course of the simulation (Section 9.6.3).

The first measure of distance captures relative position of each agent from the incident. Therefore, the hypotheses are evaluated with respect to change in location from a single reference point (incident). The second measure concentrates on change as a direct result of different model configuration which affects the behaviour of agents. Therefore, the hypotheses evaluate whether the walked distance significantly changes with the configuration.

The aim of the analysis is to identify whether the difference between any two agent distributions (with respect to the measured distance) are statistically significant. The general null hypothesis is:

> There is no difference between the means of the two distributions.

In order to identify what type of test to use for the hypotheses evaluation it is necessary to assess normality of each agent distribution. This is done by plotting the observed distributions in form of histograms against curves representing normal distributions of the same means and standard deviations. If the observed distribution is normal, the histogram should copy the progress of a Gaussian curve. Subsequently, paired Student's t-test would be used for the assessment of the hypotheses. However, if the distribution does not progress normally, non-parametric Wilcoxon signed-rank test needs to be applied.

9.6.1 Method Limitations

This approach has the following limitations:

- The change in distances does not reflect change in direction i.e, no change would be detected if the agent is located in the same distance from the incident but on a different road.
- The natural clustering around the centre of the map can affect the results of the test statistics.
- Since the *open space* preferred destinations are located in the proximity of the incident, a large number of agents (in the case of BEM and SAM configurations) have reached the destination within the course of the simulation. This results in a large number of equal distances. This natural clustering can affect the results of the test statistics evaluating the differences between BEM and SAM configurations.

Therefore, the outcomes of the statistical tests need to be carefully evaluated before any conclusions can be drawn.

9.6.2 Comparison of Distances from the Incident: Results

In this approach each agent is represented by its Euclidian distance from the incident. This approach was applied for evaluating all six hypotheses ($H01_{15min}$ - $H03_{30min}$) with respect to both case studies (Leicester and Nottingham). Graphs in Figures 9.14 and 9.15 represent comparison of the agents' distributions against Gaussian curve in Nottingham and Leicester scenarios. Images a) and d) in both figures represent the distribution of RAM InSiM configurations after 15 minutes and 30 minutes respectively. In all four cases the distribution is close to normal. However, in the rest of the cases (images b) and e) for BEM configurations and images c) and f) for SAM configurations) the observed distributions considerably deviate from the progress of the Gaussian curve. The most significant differences can be seen at histogram columns representing distances of the two open space destinations located approximately 300 meters from the incident or at zero distance reflecting that 17 % of the agents would navigate towards the incident (as defined in Table 7.10).

9.6.2.1 Evaluation of the Hypotheses

Since with exception of the RAM configurations the distributions of the agents cannot be seen as normal, the non-parametric Wilcoxon signed-rank test is applied to undertake the goodness of fit analysis. The calculations were done in SPSS statistical software (SPSS, 2009). In all cases the calculated values of the test were large than the critical values. Therefore, all the hypotheses can be rejected. This implies that the differences in the mean distances are not caused by chance but are due to the different positions of agents with respect to the incident in the two evaluated configurations.

9.6.3 Comparison of the Walked Distances: Results

This approach also makes use of the Wilcoxon signed-rank test. In this instance, the evaluated distance represents the length of path each agent walked during

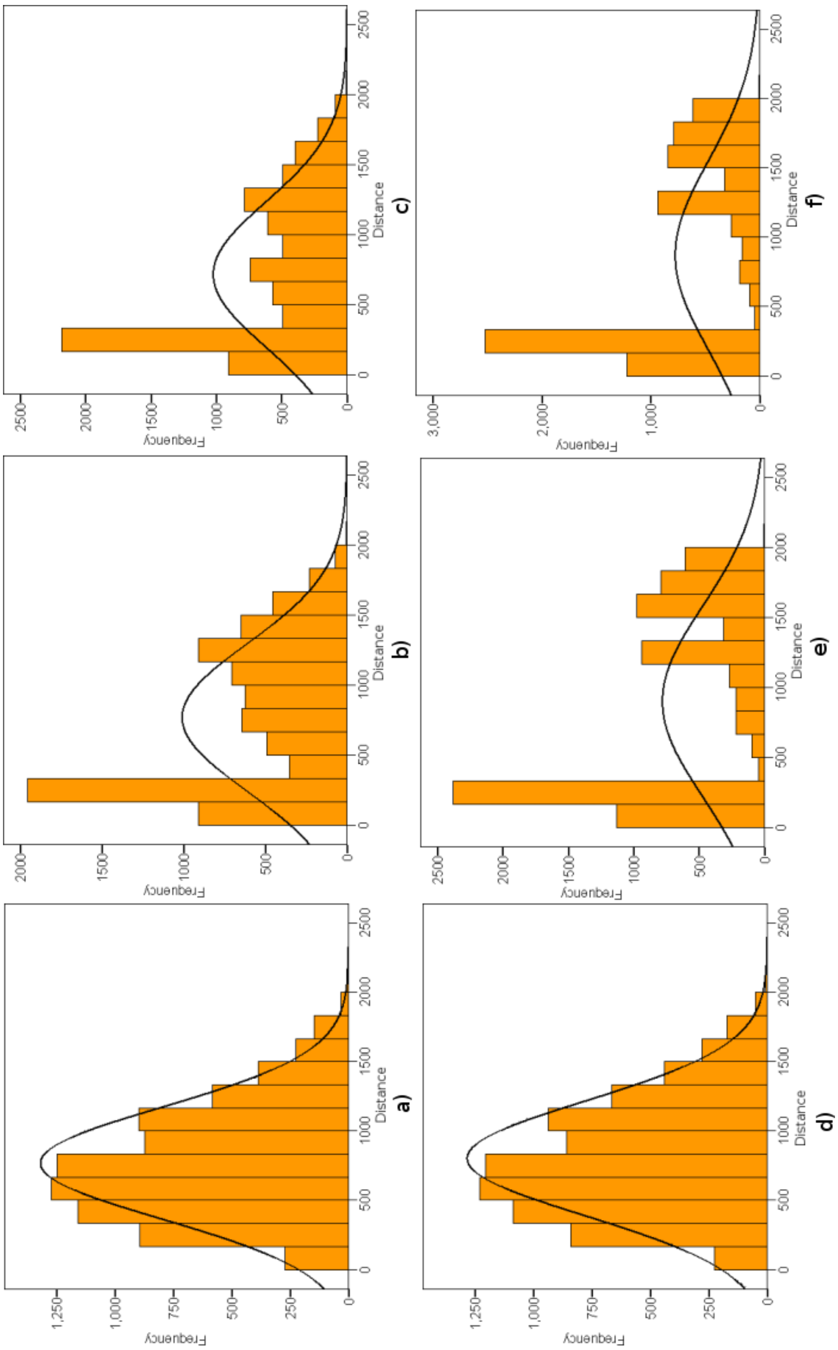

Figure 9.14: Assessment of normality for Nottingham scenarios.

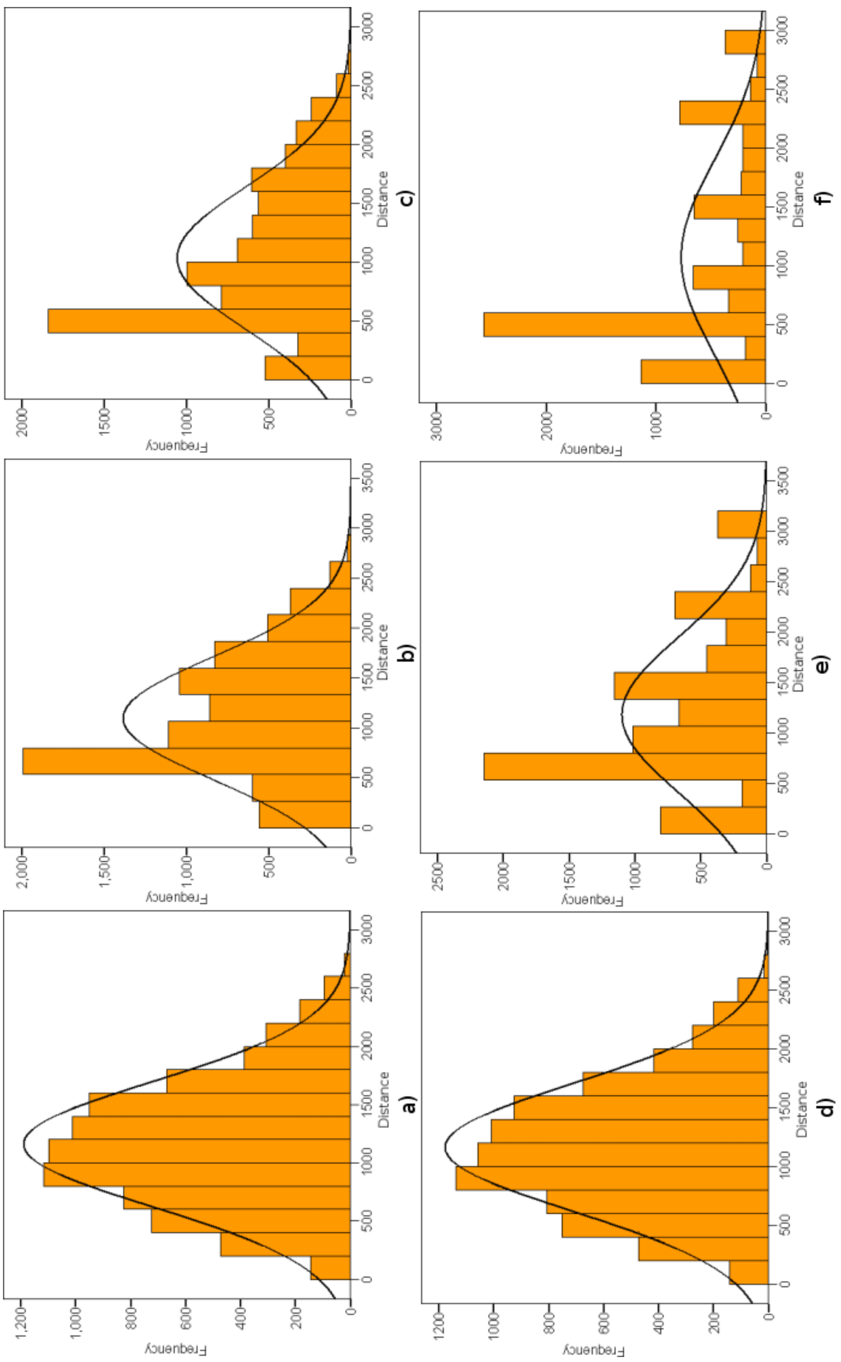

Figure 9.15: Assessment of normality for Leicester scenarios.

the course of the simulation. In contrast to the previous test, no single reference point (incident) is used. The test focuses on identification of difference between the path length predominantly caused by the differences in the agent's behaviour, i.e. model configuration. However, this approach faces similar problems as the previous one where two extreme situations can be represented with similar means.

9.6.3.1 Evaluation of the Hypotheses

Similarly to the previous assessment, in all cases the value of the test statistics is larger than the critical value. This means that with respect to the walked distances each model configuration provides a significantly different result. Therefore, all the hypotheses stated in Section 9.2 can be, from the perspective of this evaluation approach, rejected.

9.7 Model Evaluation

9.7.1 Validation

The reliability of InSiM would ideally need to be tested by simulating a scenario depicting a historical incident of a similar kind. However, the lack of information on the spatial context of pedestrian behaviour, which could be used for populating InSiM, precludes full validation of the model against real-world data.

Instead, the behaviour of agents is assessed against the information collected by the experimental studies. This is reflected in parameterisation of the model with respect to distribution of different agents behaviour, navigation preferences, selection of preferred destinations and prioritisation of different walkway categories. The values of the key InSiM parameters by which both use cases are defined are setup to reflect the distribution of the interviewed population sample. However, it must be pointed out that the model is based on information regarding hypothetical behaviour which might significantly differ from a real-life situation.

Since the simulation environment was defined with use of real geographic data its validation can determine whether it correctly represents the real-life situation. To validate the simulation environment the following procedures were conducted:

- The road network was generated from ITN layer of OS Master Map containing all navigable roads in the UK.
- Appropriate tests were taken to confirm that the generalisation of the road network did not cause any significant differences with respect to length of the network edges (see Section 7.2.5).
- The walkway categories were defined based on information extracted from the experimental studies and the roads were categorised to reflect the real world situation.

9.7.2 Verification

InSiM was developed in several iterations. After each iteration the performance of key components of the model were verified by various tests. For instance, the correctness and accuracy of agent's behaviour was tested on a small network with only one agent involved. Behaviour of this agent was tracked each simulation step to determine if its reaction corresponds with the conceptual model. In addition, reviews of the code by an experienced software engineer have been conducted on the key object classes to ensure their consistency with the design. Finally, performance of every new component was tested by the developer before the code was incorporated into the model.

9.7.3 Calibration

Calibration, also known as operational validity test, determines whether the patterns generated by the model have the desired accuracy and whether they correspond with the real-life system which is modelled (Crooks et al., 2008; Sargent, 1999). This is done by fine-tuning the model parameters to determine their best settings (Crooks et al., 2008). This calibration approach is only possible when there is data against which the goodness-of-fit test can be performed. However, such data, as in the case of this research, are not always available at the appropriate level of detail and quality.

An alternative approach to calibration is sensitivity analysis of the geo-simulation model key parameters (Sargent, 1999). The aim of the sensitivity analysis is to detect which parameters have the strongest influence on the model outcomes. This helps to identify where extra attention should be focused to define, with sufficient accuracy, the values of those parameters that have been identified as sensitive.

The sensitivity analysis tests are often conducted with extreme values to observe behaviour of the model in extreme conditions (e.g. Sargent, 1999; Schreiber, 2002). Although it represents situations that are unlikely to occur in the real-life scenario, it tests the model's robustness and behaviour outside of normal operating ranges. In addition, the sensitivity of the parameters are, due to the extreme conditions, more apparent.

The sensitivity analysis conducted in this research only focuses on identification of first order effects, i.e. how variation of a single parameter at a given time affects the overall dispersion pattern of the agents on the simulation space. This approach has been commonly used in ABM research (e.g. Batty et al., 2003; Li et al., 2008). However, the simulation results are also influenced by the second order effects caused by dependencies between two or more variables. Before such tests can be conducted the relationships between the model parameters need to be known. Due to the time constraints put on this research, such analysis are kept for thorough exploration in the further research. Hence, the adopted calibration approach reflects the influence of the first order effects only.

In order to speed up the calibration procedures the number of agents have been reduced to 1,000 and the simulation duration corresponds to 15 minutes scenario when appropriate. In addition, the sensitivity analysis is only conducted on the Nottingham city map and on SAM configuration unless the test requires also data generated by the remaining two configurations. The values of the model parameters that are not tested remain the same as defined in the use case scenarios. The sensitivity analysis is adopted for the model parameters that form the key behavioural characteristics of InSiM. These are:

- simulated time period (*maxSimualtionDurationInMinutes*)
- number of agents (*numAgents*)
- agent's moving speed (*agentMaxMovementKilometersPerHour*)
- distribution of navigation preferences (*wide walkways, narrow walkways, shortest path*)
- walkway weights (*narrow walkways, wide walkways, dual carriageways, pedestrianised streets*)
- distribution of destination preferences (*home, incident area, open space*)
- communication distance (*agentCommunicateIncidentDistance*)
- seconds represented in one simulation step (*simulatiSecondsPerTick*)
- incident awareness radius (*incidentAwarenessRadius*)

Visual analysis of agent densities provided the most transparent information for evaluation of the hypotheses. Therefore, the same approach was used for assessing the outputs of the sensitivity analysis. In addition, in some tests the proportion of agents aware of the incident and agents that have reached their destinations is extracted to assess how the variation of the parameter affects the exchange of the information and consequent reaction. In the following sections, each of the listed parameters is tested and the effects of its variations on the agents' dispersion pattern are evaluated.

9.7.3.1 Simulated Time Period

The simulated time period is related to the time interval that is simulated by InSiM. The calibration test focuses on evaluating effects of simulated time period on the:

- time the simulation took to execute (*real time*);
- behaviour of agents with respect to the exchange of information about the incident.

The test was conducted for all three InSiM configurations. The maximum simulated time period was setup to correspond to the time in which at least 95 % of the agents aware of the incident have reached their destinations.

The results of the tests are summarised in Table 9.4. The percentage of agents aware of the incident with respect to all agents is depicted in the *Aware agents* column. The *On destinations* column displays the percentage of aware agents that have reached the preferred destination within the simulated time period. The results are graphically represented in Figure 9.16.

Image a) (Figure 9.16) illustrates the dependency of the time the simulation took to execute on the length of the represented simulation time period. The lines depicting BEM and SAM configurations indicate that the relationship is of a linear nature. The approximately 1 minute difference apparent at the 60 minutes simulated time period could have been caused by additional parallel

Configuration	Simulated time period [min]	Real time [min:sec]	On destinations [%]	Aware agents [%]
RAM	5	00:00.3	N/A	N/A
BEM	5	00:14	20	18
SAM	5	00:14	15	17
RAM	10	00:00.7	N/A	N/A
BEM	10	00:38	21	35
SAM	10	00:47	23	45
RAM	20	00:02	N/A	N/A
BEM	20	01:39	47	66
SAM	20	01:41	44	68
RAM	30	00:04	N/A	N/A
BEM	30	03:01	80	75
SAM	30	03:02	71	76
RAM	40	00:03	N/A	N/A
BEM	40	02:59	93	76
SAM	40	02:57	87	79
RAM	50	00:03	N/A	N/A
BEM	50	03:50	96	81
SAM	50	03:39	95	81
RAM	60	00:03	N/A	N/A
BEM	60	04:20	97	79
SAM	60	05:08	98	79

Table 9.4: Effects of varying length of the simulated time period on the InSiM behaviour.

	Real time [hh:mm:ss]		
Number of agents	RAM	BEM	SAM
100	00:00:00.1	00:00:02	00:00:01
500	00:00:00.4	00:00:25	00:00:24
1,000	00:00:01	00:01:21	00:01:25
1,500	00:00:02	00:03:16	00:03:50
3,000	00:00:05	00:11:28	00:14:17
5,000	00:00:08	00:27:57	00:24:58
8,000	00:00:13	01:09:43	01:02:23
10,000	00:00:18	01:33:07	01:32:30
15,000	00:00:27	03:20:21	03:06:15

Table 9.5: Effects of number of agents on simulation speed.

processes running on the PC simultaneously with the simulation. Since the reasoning of RAM agents is less complex than the remaining two configurations, the simulation runs faster (several seconds compared to minutes or hours).

Image b) represents how extending the length of the simulation time period affects the number of incident aware agents. Since in RAM configuration the concept of aware agent is not implemented, the graph only depicts the dependency between the two parameters in BEM and SAM configurations. A steep increase of aware agents is apparent up to 30 minutes after that the amount of aware agents does not change (maximum span is 6 %).

Image c) represents that in 50 minutes 96 % of aware agents in BEM have reached their destination, 95 % in SAM respectively. This indicates the time when InSiM reaches equilibrium, i.e. no significant changes to the outcomes of the simulation can be, with respect to the parameter under investigation, observed.

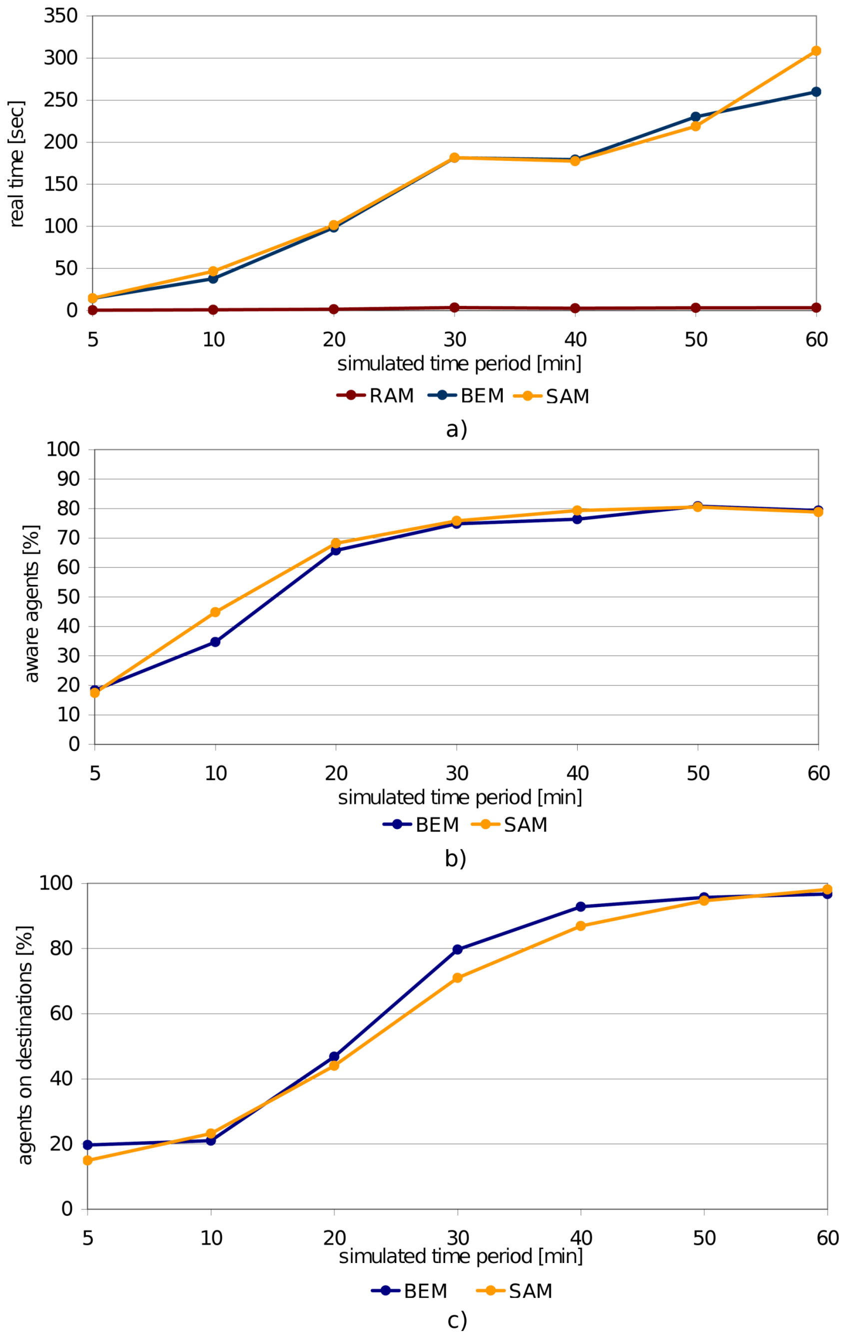

Figure 9.16: Effects of simulated time period on behaviour of InSiM.

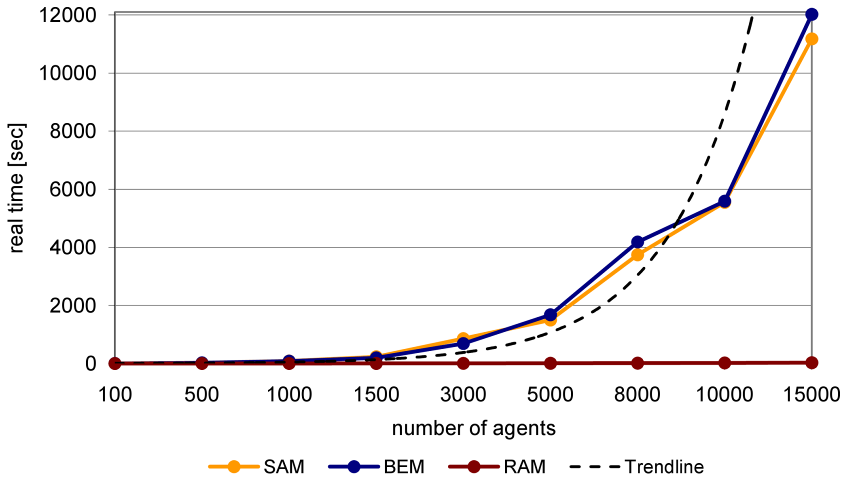

Figure 9.17: Effects of number of agents on the behaviour of InSiM.

9.7.3.2 Number of Agents

This test assesses to what extent the number of agents influences the time the simulation took to execute. All three InSiM configurations were tested to identify whether the effects were influenced by the complexity of agent's behaviour. The results are summarised in Table 9.5 and graphically represented in Figure 9.17. The graph demonstrates that the simulation time (*real time*) increases almost exponentially with the number of agents. For comparison the black dashed trendline represents exponential Equation 9.7.1.

$$y = 2.0967e^{1.0399x} \tag{9.7.1}$$

While running the RAM configuration, even with a large number of agents (up to 15,000), took several seconds, the BEM and SAM configurations required a similar but significantly longer time to complete. On average, one simulation minute for 15,000 agents took approximately 13 minutes to process (BEM configuration). These results indicate that for real-time application the approximate number of agents would need to be 3,000 for BEM and SAM configurations (subject to using the same computer with identical initial simulation conditions).

9.7.3.3 Speed

This calibration test concentrates on identifying what effect changes in agent's moving speed have on:

- the behaviour of agents represented by the proportion of:
  - aware agents to the whole agent population, and
  - aware agents that have reached their destinations within the simulated time period;
- the overall dispersion pattern of the agents on the simulation space.

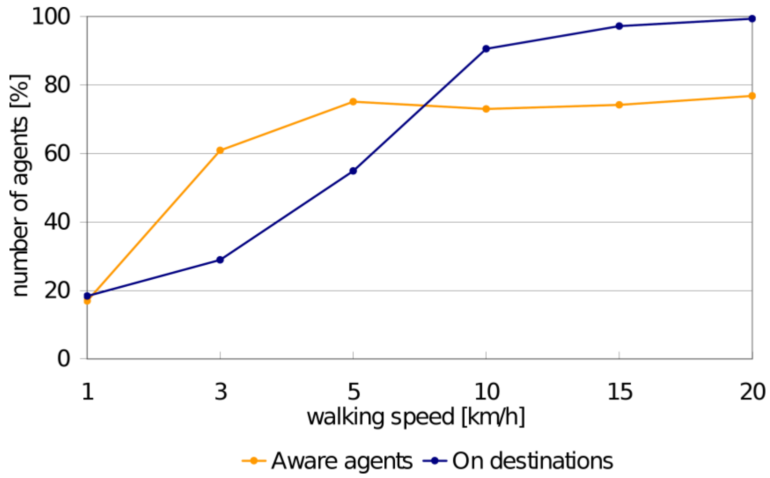

Figure 9.18: Effects of moving speed on the dispersion pattern of agents.

Table 9.6 summarises the calibration results with respect to the changes to the two criteria according which the agent's behaviour is evaluated. The relationships are also graphically displayed in Figure 9.18.

The effects were tested in five simulations with the moving speed ranging from 1 to 20 km/h (*testAs* - *testEs*). The slowest walking speed is defined in such a way to allow for possible short stops (corresponds to average speed of 0.28 m/s). The maximum walking speed is defined in correspondence with Nilsson and Thorstensson (1989) who claim that 6 m/s (20 km/h) is an average running speed of a healthy male.

Test ID	Image in Figure 9.19	speed [km/h]	Aware agents	On destinations	Aware agents [%]	On destinations [%]
scenario	a)	3	609	176	61	29
testAs	b)	5	751	412	75	55
testBs	c)	10	730	661	73	91
testCs	d)	15	742	721	74	97
testDs	e)	20	768	763	77	99
testEs	f)	1	169	31	17	18

Table 9.6: Definition of tests assessing effects of moving speed on agent behaviour.

The number of aware agents does not significantly change after the moving speed is setup to 5 km/h or faster (varying between 73 - 77 %). It also indicates that if the moving speed is setup to 15 km/h, 97 % of aware agents would reach their preferred destinations in 15 minutes after the blast.

The effects of the speed on the overall dispersion pattern can be observed by comparison of densities depicted in Figure 9.19. The same method was used for creation of the density surfaces as defined in Section 9.4. However, distribution of the colours is different to better illustrate the differences (see legend in Figure 9.20.

The most apparent difference occurs at the locations depicting exit points towards home. In the walking speed defined in the scenario (image a)) agents have not reached these destinations within 15 minutes after the blast. However, higher densities can be observed in image b) which depicts walking speed of 5 km/h. Moreover, images c) - e) demonstrate that the densities on these locations increase with the increasing moving speed of the agents. Image f) depicts the scenario where the moving speed of the agents is set to minimum. Due to such slow movement, no high density spikes are visible at the preferred destinations (not event those located in the map central area). This indicates that large number of agents are still situated along the way.

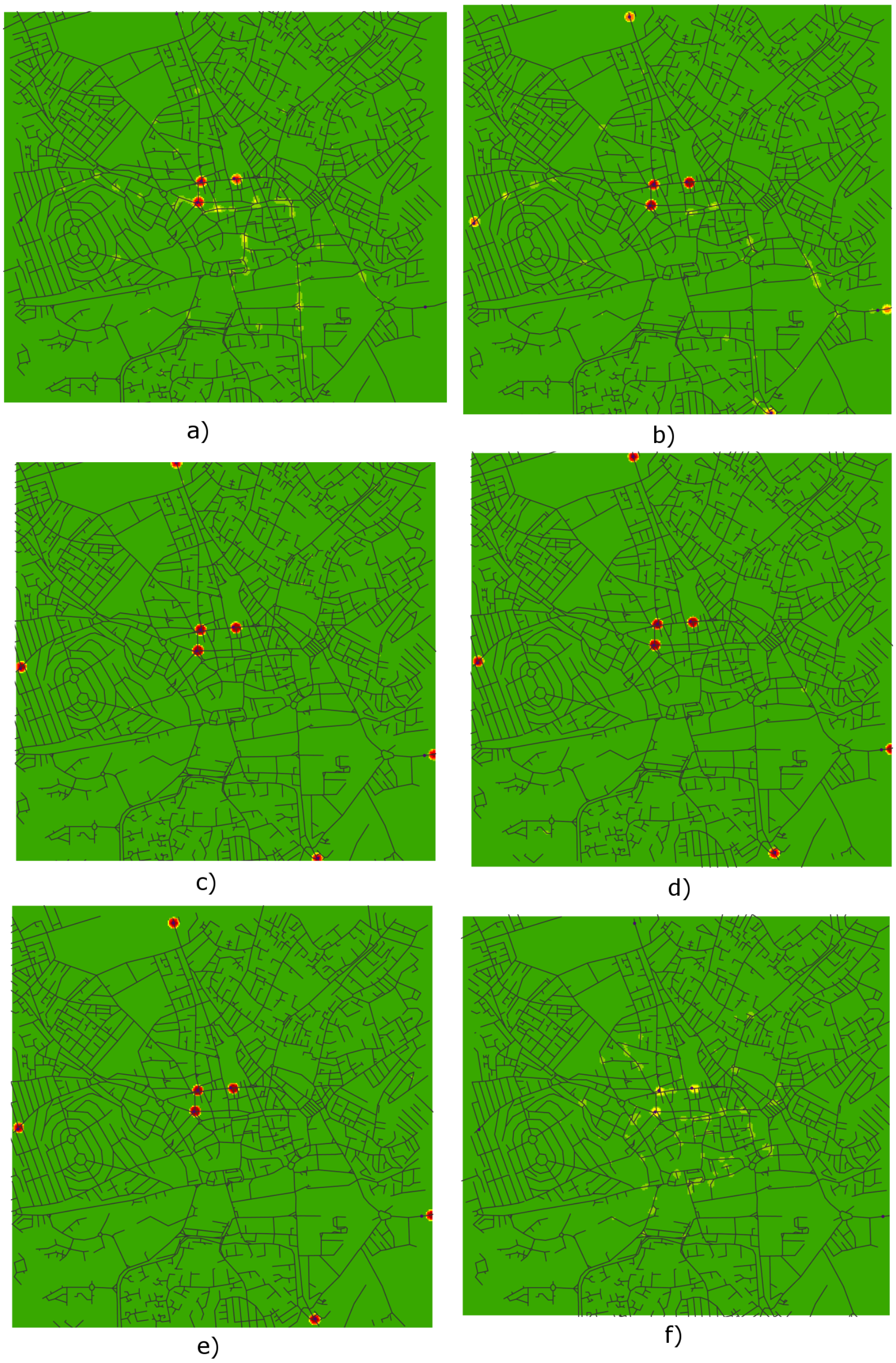

Figure 9.19: Agent densities of different moving speed.

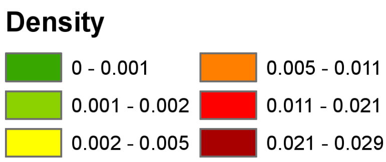

Figure 9.20: Density categories.

It can be concluded that the speed of agents does have an effect on the final dispersion patterns. However, the effects of a faster moving speed are only apparent in shorter time periods (subject to initial distance of the agents from the preferred destinations).

9.7.3.4 Distribution of Navigation Preferences

The navigation preferences are related to the prioritisation of some roads over others when deciding the most suitable route towards the preferred destination. This was defined as the walkway preference of narrow walkways, wide walkways, or shortest path. In the two case studies by which InSiM was tested the distribution of the agent population among the categories of navigation preferences was directed by the distribution of the sample population that was interviewed in the experimental studies.

Tests depicting five extreme situations were conducted to obtain data based on which the effects of the distribution on the agents' dispersion patterns can be assessed. The settings of the walkway preferences are summarised in Table 9.7. Tests *test1* - *test3* demonstrate the situation where all agents share the same preference, while *test4* represents an equal distribution among the agent population. Figure 9.21 depicts densities representing the distribution of agents on the simulation space.

The lack of narrow roads at the SE corner of the map caused similar distribution in that area on image b) (narrow road preference) as on the remaining images. However, differences can be seen in the city centre and the area near the West exit point. Differences between image a) and c) are not as apparent since 63 % of the agents in the scenario follow the wide walkways. Variances between image a) and d) indicate differences between BEM and SAM configurations since in image d) all agents are following the shortest path. While in image a) higher densities are localised towards the wider walkways, agents in

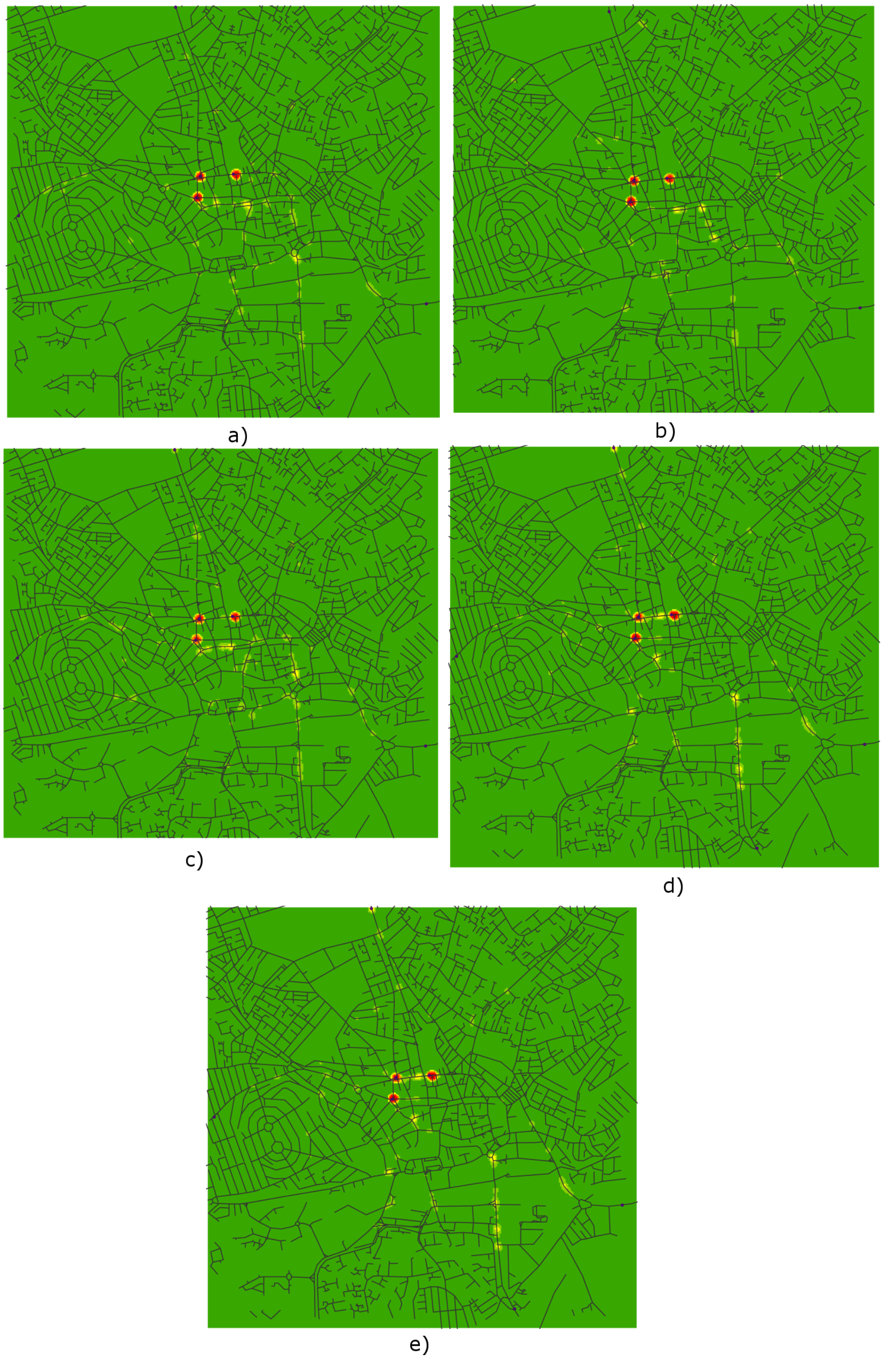

Figure 9.21: Agent densities of different distributions of navigation preferences.

Test ID	Image in Figure 9.21	Walkway preference Narrow	Wide	Shortest path
scenario	a)	25	63	12
test1	b)	100	0	0
test2	c)	0	100	0
test3	d)	0	0	100
test4	e)	33	33	34

Table 9.7: Definition of tests assessing effects of walkway preference distributions on the simulation results.

image e) are more dispersed around the area. The differences are most apparent at the West and South direction.

The differences in dispersion patterns caused by alteration of the navigation preferences are not as apparent as, for instance, those caused by the moving speed modification. However, local variances can, as demonstrated, be observed.

9.7.3.5 Walkway Weights

The walkway weight refers to the constant by which length of each road segment is multiplied. The weight reflects the road characteristic which the agent considers when constructing the most suitable route toward the preferred destination. The walkway weights are set for each navigation preference category which reflects the prioritisation of one road type over another.

This sensitivity analysis tests the effect the walkway weights have on the overall dispersion pattern of the agents. For this purpose four tests were carried out. Each test represents an extreme situation where:

- the maximum weight makes the road segment twice as long as its actual size ($w = 2$; e.g. 50 m distance becomes 100 m long);
- the minimum weight shortens the length of the road segment to a tenth of its original size (w = 0.1; e.g. 50 m distance becomes 5 m long).

Test ID	Image in Figure 9.22	Navigation preference	Wide walk-way	Narrow walk-way	Dual c-way	Pedestrian street
scenario	a)	Wide	0.5	1.5	1	1.5
		Narrow	1	0.5	1.5	1.5
testA	b)	Wide	0.1	2	1	1.5
		Narrow	2	0.1	1.5	1.5
testB	c)	Wide	0.1	2	2	2
		Narrow	2	0.1	2	2
testC	d)	Wide	0.1	1	1	1
		Narrow	1	0.1	1	1
testD	e)	Wide	0.5	1.5	2	2
		Narrow	1	0.5	2	2

Table 9.8: Definition of tests assessing effects of walkway weights on the simulation results.

The minimum value indicates strong attraction towards walkways of navigational preference. The disfavour with certain walkway type is overruled once the alternative path becomes once longer than the original one.

The weight settings for the tests are summarised in Table 9.8. The tests are setup to reflect the following:

testA The weight of the walkway type preference is set to the minimum (w = 0.1) to strengthen the preference. The weight of the walkway of the least preference is set to the maximum value (w = 2). The remaining weights are kept the same as they were for the case studies (*scenario*).

testB The weight of the walkway type preference is set to the minimum, while all the remaining weights are set to the maximum value.

testC The weight of the walkway type preference is set to the minimum and no weights are applied to the remaining walkway types.

testD The weights of the walkway types of the most and the least preference are kept the same as defined in the case studies, while the weights of the remaining walkway types are set to the maximum value.

Figure 9.22 shows agent densities generated by the sensitivity analysis tests. Differences in the dispersion patterns can be observed between images a) and

Test ID Image in Figure 9.23	scenario a)	testAt b)	testBt c)	testCt d)	testDt e)
Home	46	100	0	0	34
Incident area	16	0	100	0	33
Open space	38	0	0	100	33
North direction	11	25	0	0	8
South direction	11	25	0	0	8
East direction	12	25	0	0	9
West direction	12	25	0	0	9
Incident area	16	0	100	0	33
Open space 1	19	0	0	50	17
Open space 2	19	0	0	50	16

Table 9.9: Definition of tests investigating effects of prioritisation among preferred destinations on the dispersion pattern.

b). Higher density values forming on the centrally located street leading in a WE direction can be observed in images b), c) and d). This is caused by the large number of agents (63 %) preferring the *wide walkways*. Although some differences can be observed between image a) and e) they are mostly of a local nature. This can be caused by small number of *pedestrianised streets* or *dual carriageways* in the city centre providing agents with alternative options.

The comparison of the density surfaces reveals that definition of the walkway weights have an effect on the overall dispersion pattern of agents. Even though this effect is mainly observable at the local level, it should not be neglected. Since the weights are connected with the different road types, the resulting dispersion pattern is influenced by the layout of the city and the proportions of the streets of the specific type in the city centre.

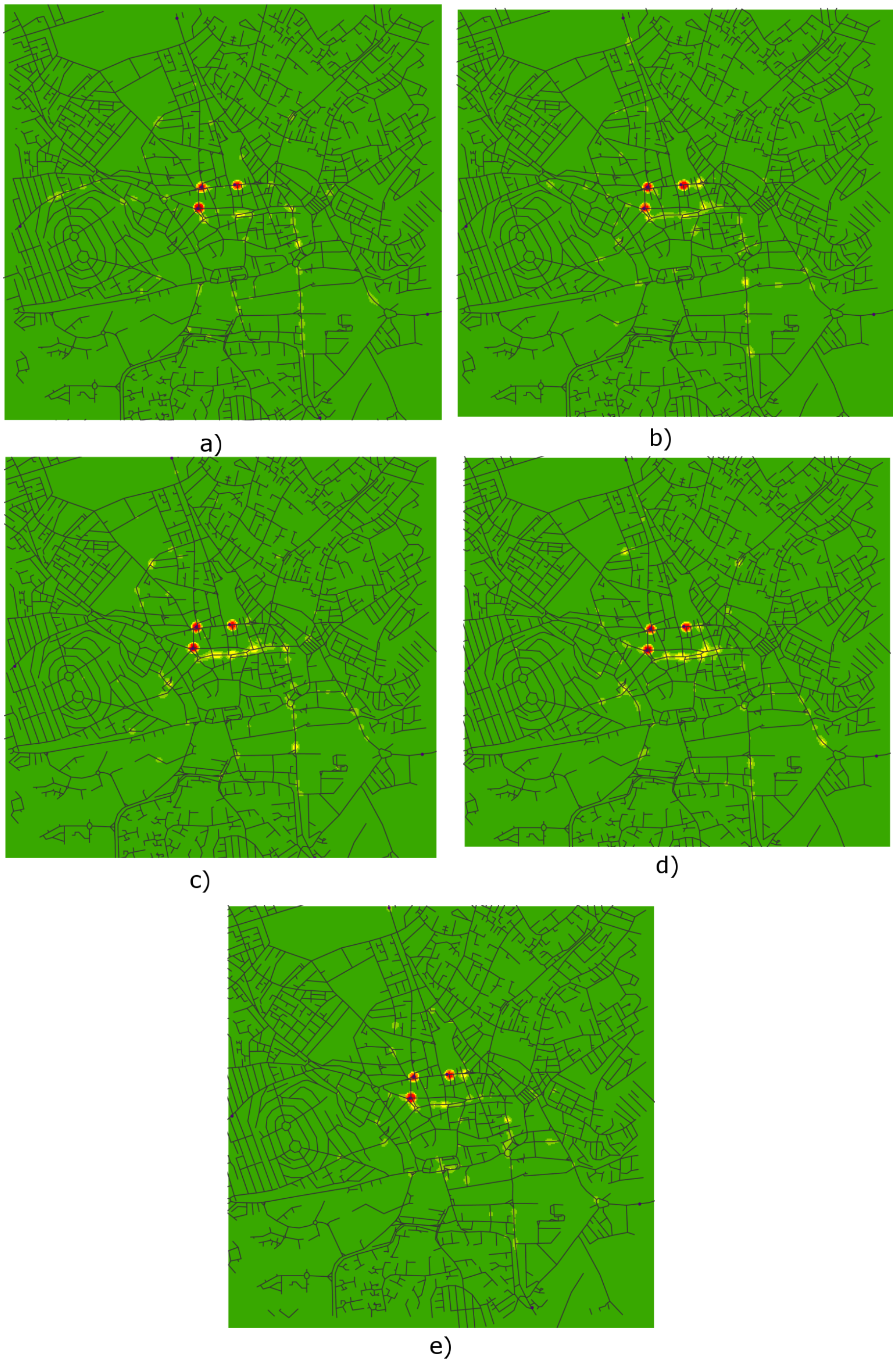

Figure 9.22: Agent densities of different distributions of walkway weights.

9.7.3.6 Distribution of Destination Preferences

In InSiM, once an agent becomes aware of the incident its behaviour switches to following the most suitable route towards a specific destination. In the conceptual model, the locations of the destinations on the simulation space of InSiM are defined. This calibration test assesses the sensitivity of InSiM to changes of:

- destination preference, and
- locations of the destinations on the simulation space.

Four tests (Table 9.9) were setup to represent the different extreme situations where all agents in tests *testAt* - *testCt* move towards a single destination type. Test *testDt* is defined to depict a situation where each destination type is selected by an equal proportions of agents. As *home* and *open space* destinations are represented in InSiM by more than one place, the distribution of agents is proportionate to the number of locations. The results of the sensitivity analysis are graphically displayed in Figure 9.23.

Visual comparison of the images reveals differences in the densities. As a consequence of the *home* destinations being located at the map edges, clear density clusters on roads towards such places are visible in image b). High density spikes are formed at centrally located destinations in images c) and d). Image e) indicates that the large proportion of agents preferring *incident area* and *open space* locations have reached their destination while remaining agents are still walking towards *home* (no clusters are formed at the edges of the map). The analysis indicates that InSiM is highly sensitive to changes of the preferred destination locations. This is a consequence of the definition of agent's behaviour which is represented by navigation towards these locations.

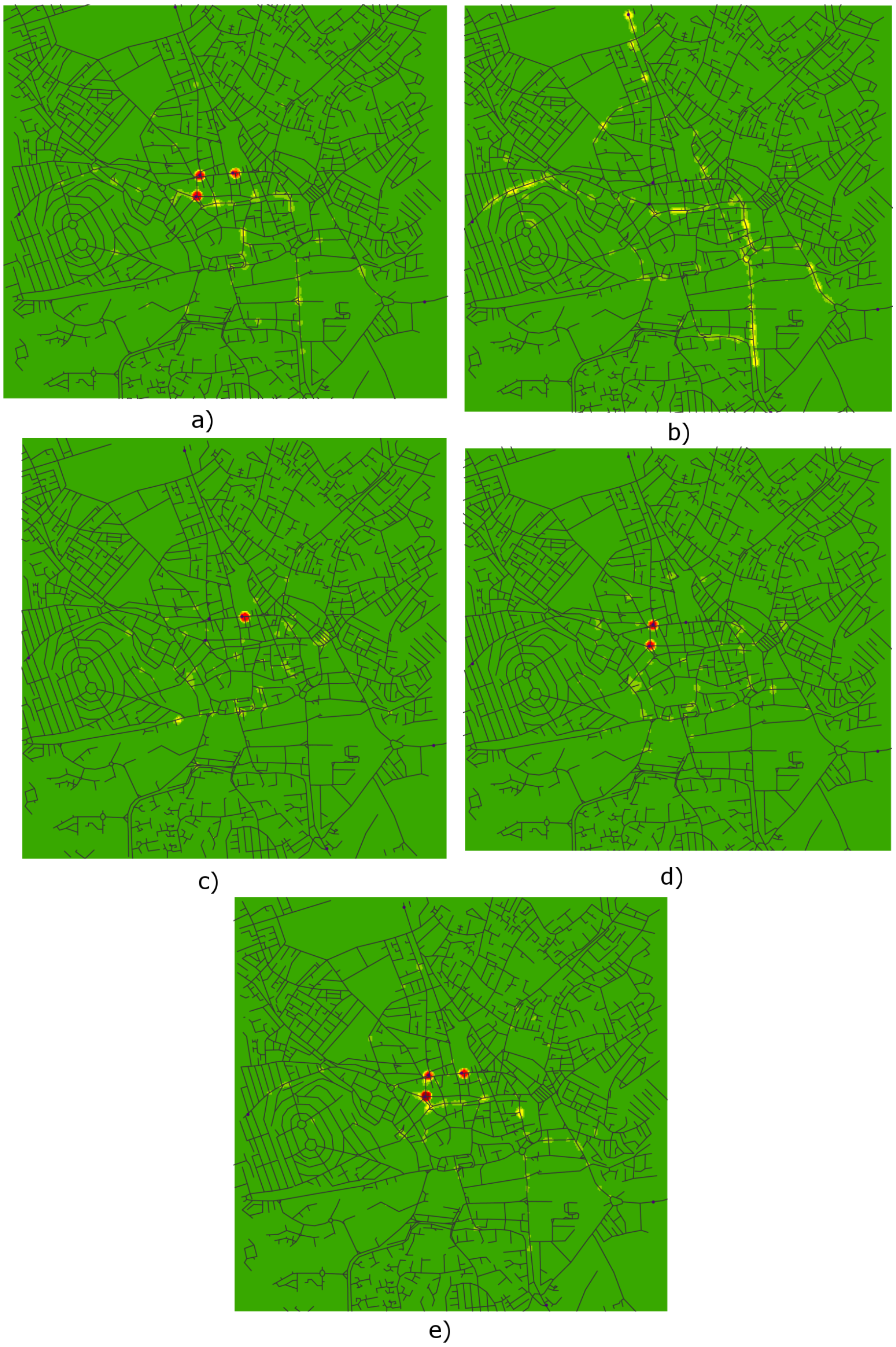

Figure 9.23: Agent densities of different preferred destinations.

Test ID	Image in Figure 9.25	Communication distance [m]	Aware agents [%]	On destinations [%]
scenarios	a)	10	61	29
testAcom	b)	2	26	34
testBcom	c)	5	54	29
testCcom	d)	15	69	31
testDcom	e)	20	67	27
testEcom	f)	30	75	33

Table 9.10: Definition of tests assessing effects of communication distance on the dispersion pattern.

9.7.3.7 Communication Distance

This test concentrates of evaluating how variation of distance within which agents can communicate affects their final distribution. The radius of a circle representing the agent's neighbourhood is adjusted to between 2 and 30 metres. The actual tested values are summarised in Table 9.10 together with percentages of agents that are aware of the incident and those reaching their destinations within the 15 minutes period. The percentages are graphically represented in Figure 9.24 and the dispersion patterns as densities in Figure 9.25.

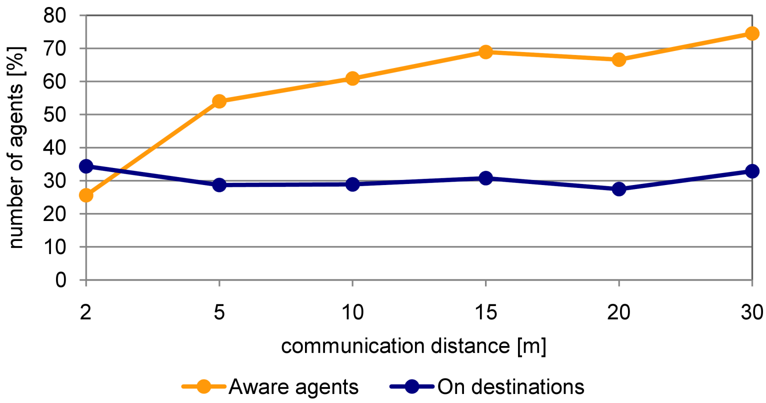

Figure 9.24: Effects of communication distance on agents' behaviour.

The graph (Figure 9.24) indicates that the number of agents at the destination is not influenced by the variation of the communication distance. With a longer communication distance agents have a better chance of meeting others. Therefore, the information about the incident is transmitted faster (increased number of aware agents).

The lower number of aware agents is reflected in image b) by smaller density clusters on the central preferred destinations and the streets leading towards the outskirts of the city. Changes in densities exist between images b) and c) where the communication distance has been enlarged by an additional 3 metres. Although the remaining tests demonstrated some local changes, their extent is less apparent. Based on the visual comparison of the density maps, it can be concluded that the resulting dispersion pattern is partly influenced by the size of the communication distance between agents. However, the influence is not, in this case, as strong as in other parameters.

9.7.3.8 Seconds Represented in One Simulation Step

This test focuses on evaluating the effect of altering the number of seconds (time interval) represented in one simulation step. In the use case scenarios one simulation minute (representing one minute of the explosion aftermath) was divided into twelve intervals. This means that agents could communicate every 5 seconds corresponding to a distance of 4 meters. In the sensitivity analysis the time period in one simulation step ranges from 1 second to 1 minute. The effects of such changes are captured with respect to number of aware agents and agents located on the preferred destinations. The definitions of the sensitivity analysis tests are summarised in Table 9.11. Observed effects are represented as a graph in Figure 9.26 and the agent densities in Figure 9.27.

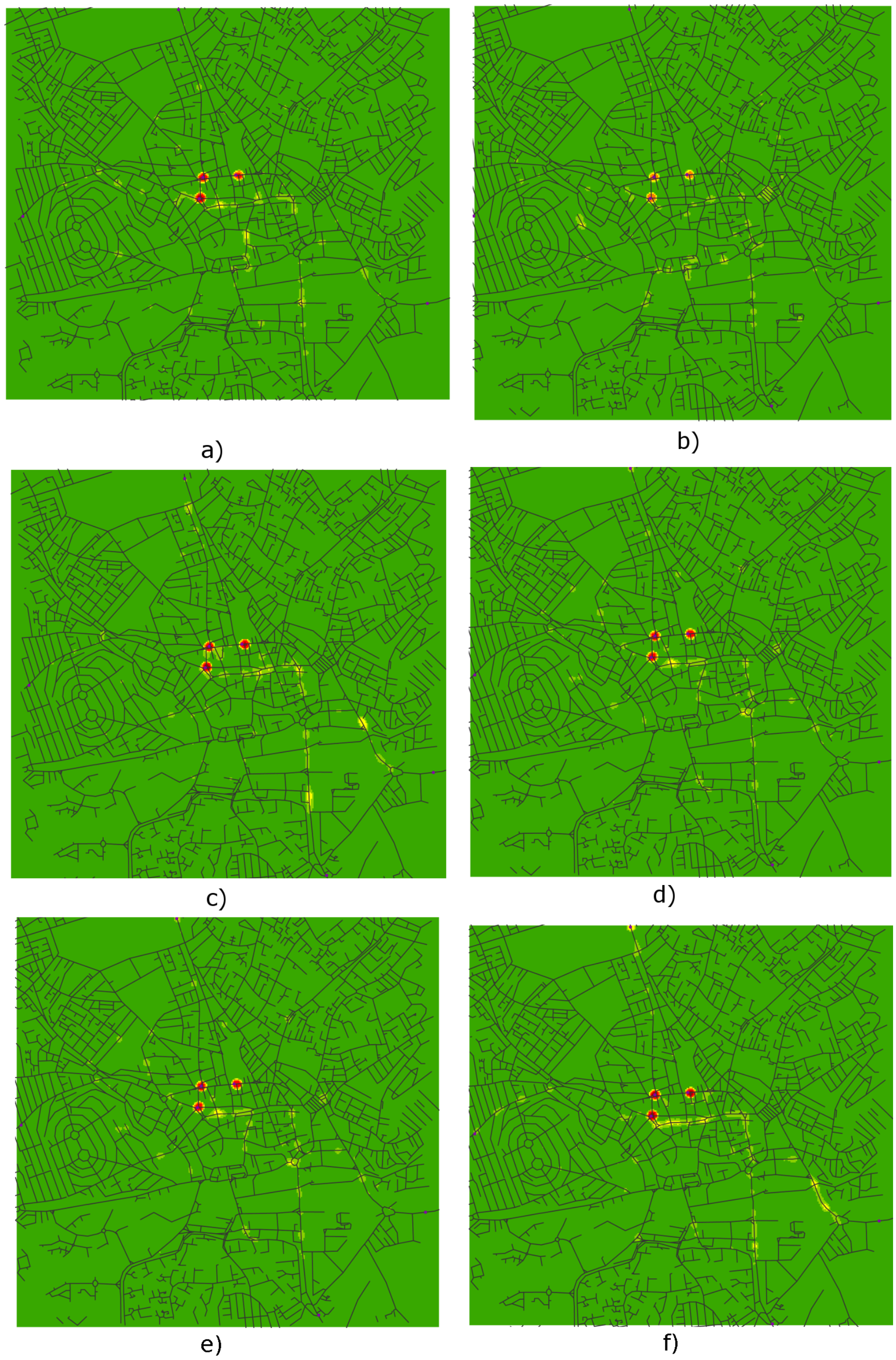

Figure 9.25: Agent densities of different communication distances.

Test ID	Image in Figure 9.27	seconds per simulation step	simulation steps per minute	meters per simulation step	Aware agents [%]	On destinations [%]
scenario	a)	5	12	4	51	31
testAtic	b)	1	60	0.8	69	28
testBtic	c)	10	6	8	55	26
testCtic	d)	20	3	16	44	29
testDtic	e)	30	2	24	33	29
testEtic	f)	60	1	48	5	23

Table 9.11: Definition of tests assessing effects of altering number of seconds represented in one simulation step.

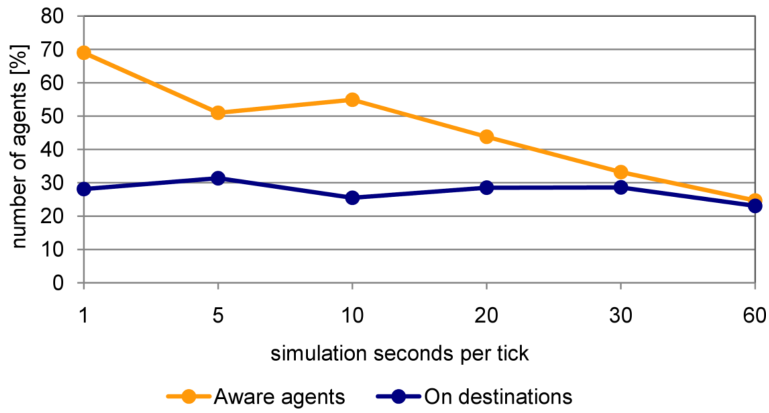

Figure 9.26: Effects of altering number of seconds represented in one simulation step.

The graph in Figure 9.26 illustrates that the number of aware agents decreases as the time interval per one simulation step increases. This indicates that agents that pass each other within the period of one simulation step do not always have a chance to exchange the information. This happens in situations where agents are located at the maximum communication distance. For instance, in *testEtic* an agent updates its state after every 48 metres. An agent bases its decision on information collected at its final position. Agents that were met during the progress of this simulation step (within the 48 metres distance) are omitted if their position, after the end of the simulation step, is further away than the communication distance.

The miscommunication problem is reflected in the density maps (Figure 9.27). The biggest difference is apparent at the density spikes on the central destina-

Test ID	Image in Figure 9.29	Incident awareness radius [m]	Aware agents [%]	On destinations [%]
scenario	a)	120	61	29
testAaw	b)	50	54	30
testBaw	c)	100	64	26
testCaw	d)	150	65	30
testDaw	e)	200	62	29
testEaw	f)	250	68	32
testFaw	g)	300	71	31

Table 9.12: Definition of tests assessing effects of incident awareness radius extent on the dispersion pattern.

tions. The density level decreases with increasing interval between simulation steps. Therefore, it can be concluded that the dispersion pattern of agents is sensitive to the time interval which is represented in one simulation step.

9.7.3.9 Incident Awareness Radius

The effects of altering the extent of the incident awareness circle are evaluated at distances ranging from 50 meters to 300 meters. The minimum distance is selected in accordance with the threshold of severe wounds caused by the backpack size bomb which is considered as the explosive device in the use case scenarios (FEMA, 2003). The effects are evaluated with respect to changes of the agents' behaviour, and the overall dispersion pattern of agents on the simulation space. Table 9.12 summarises the settings of the sensitivity analysis tests and their outcomes regarding the percentages of aware agents.

The graph in Figure 9.28 indicates that the number of aware agents and agents located on the preferred destinations is almost constant across the range of the incident awareness radius values. This means that the extent of the awareness circle does not have an effect on the changes of agent's behaviour.

Several differences can be observed at the central area on the density maps represented in Figure 9.29. The density values on the streets in the proximity of the incident varies with the extent of the awareness circle. It can be therefore

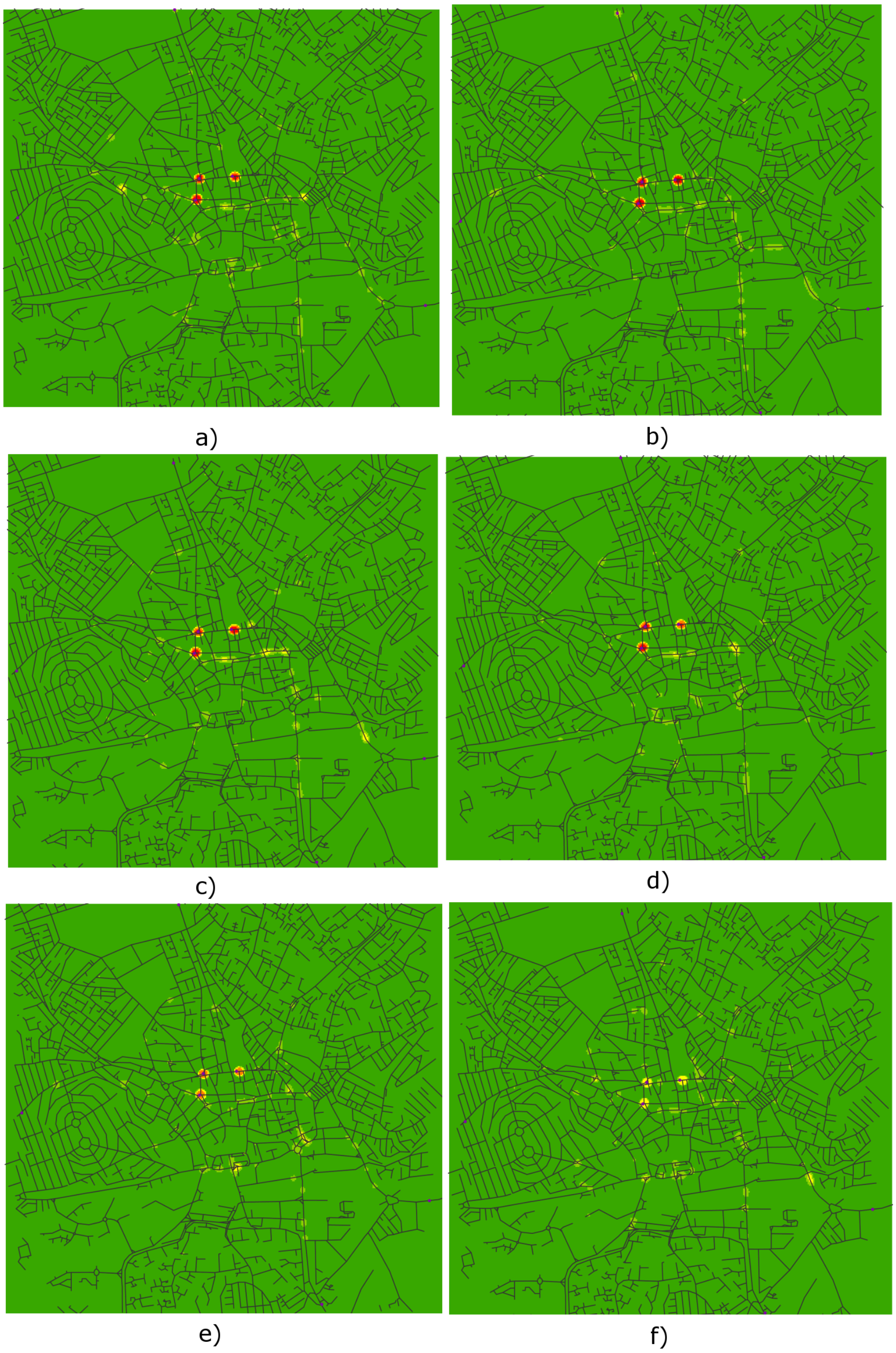

Figure 9.27: Agent densities of different number of seconds represented in one simulation step.

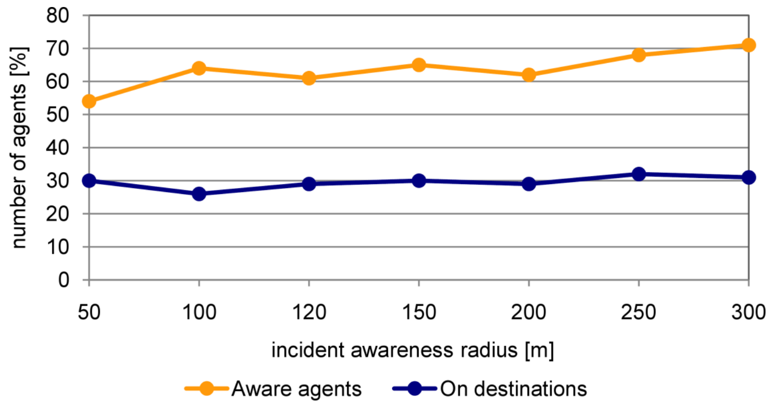

Figure 9.28: Effects of altering incident awareness radius on agents' behaviour.

concluded that even though the incident awareness radius parameter does not have a significant effect on number of aware agents, some differences in the agents' dispersion pattern exist. This might be a consequence of the random process applied for the distribution of agents to the different categories of preferences (e.g. destinations, navigation, etc.).

9.8 Conclusions

The aim of this chapter was to report analysis of data generated by InSiM and evaluate its functionality through validation, verification and calibration. InSiM is developed in three configurations where each advances the agent's behaviour with additional considerations. Effects caused by the different configurations were assessed through detection of changes in the agents' dispersion pattern on the simulation space.

Due to the number of constraints put on the generated data, use of quantitative approaches for comparison of the different agent distributions was found to be highly limited. Alternative approaches also posed difficulties. Therefore, instead of reporting findings from application of a single approach, several different techniques were tested to obtain different views of the data. Strengths and weaknesses of each technique were discussed to examine their suitability

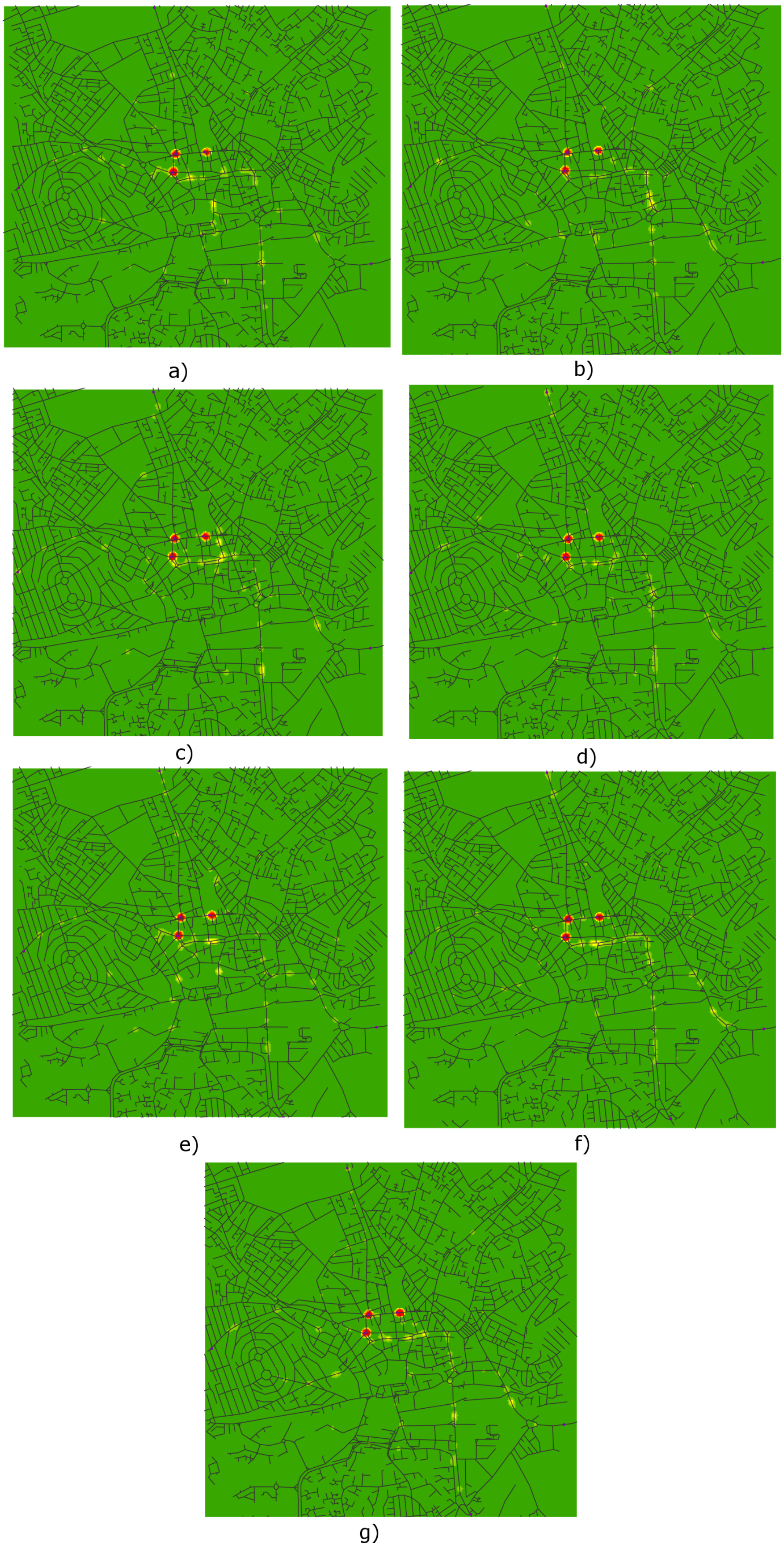

Figure 9.29: Agent densities of different awareness radius.

for the purposes of this study.

Out of seven tested analytical approaches only four provided results of desired quality. These techniques were:

- visual analysis of density maps depicting agents' dispersion pattern;
- image differencing applied on the density maps;
- goodness-of-fit test for comparison of distances of agents from the incident;
- goodness-of-fit test for comparison of distances agents walked during the course of the simulation.

These techniques were used to test the six null hypotheses stated in Section 9.2. The findings of the qualitative and quantitative evaluation lead towards the hypotheses rejection. The Wilcoxon signed-rank statistical tests revealed that any two of the agents' datasets come from different distributions. This indicates that incorporation of additional agent's characteristics and considerations affects the overall behaviour of the simulation model. Such finding suggests that every change to agent's behaviour has an effect on the outcomes of the simulation. Hence, more attention should be given to incorporation of real-life information into the definition of the geo-simulation models.

The chapter also reported approaches adopted for evaluation of InSiM functionality. The model was validated with respect to information obtained from the experimental studies. Several tests were conducted to assess the accuracy of the simulation environment. Verification was conducted by testing each newly implemented program component. An extensive part of this chapter was devoted to calibration in the form of sensitivity analysis of InSim's nine key parameters. The results of the tests were evaluated by:

- visual analysis of density maps;
- graphs representing the relationship between the evaluated parameter and the number of
  - aware agents, and
  - agents that reached their destination in the course of the simulation.

Chapter 10

Discussion

10.1 Introduction

If a geo-simulation model is to represent a real-world system, it needs to possess its characteristics and behaviours (Gimblett, 2002). This research focused on identifying and resolving issues and problems that are related to incorporation of real-life data and domain knowledge into geo-simulation models developed for disaster management.

This chapter discusses the research findings and reviews the methodology proposed in Chapter 3. It is organised into five sections:

- Section 10.2 presents practical and conceptual issues that emerged from the research. It also discusses the impact of these issues on the research project and how they were addressed.
- Section 10.3 evaluates the proposed and applied methodology using the same set of questions established in Section 2.3.2 for assessing competence and integrity of existing agent-based models for disaster management.
- Section 10.4 assesses the potential usability of InSiM within the context of disaster management with respect to its purpose, type, and relevance.
- Section 10.5 discusses the general findings of the research in the context of

Simulated time period	Configuration	Real time [hh:mm:ss]	
		Nottingham	Leicester
15 minutes	RAM	00:00:15	00:0014
	BEM	01:04:44	01:00:25
	SAM	00:54:13	00:52:53
30 minutes	RAM	00:00:29	00:00:24
	BEM	02:29:17	02:19:16
	SAM	01:39:36	01:28:42

Table 10.1: Summary of simulation times.

the bigger scientific picture. It also argues that the contribution of this research is to improve the state-of-the-art of ABM in disaster management.

- Section 10.6 summarises the discussion.

10.2 Practical and Conceptual Issues

The following paragraphs discuss a set of issues which have a significant impact on the application of ABM to disaster management. The focus of the discussion is on problems related to realistic representation of the real-life system that is modelled.

10.2.1 Computational Issues

Model complexity was limited by the performance of the computer on which the simulations ran (dual core processor 1.6GHz, 2GB of RAM). Table 10.1 summarises run-times for both scenarios within the two defined time intervals. It indicates that with the exception of the RAM configuration the simulation could not be done in real time. For operational purposes more powerful computers would be needed to minimise the processing time. Alternatively, the process would need to be distributed across several different PCs as was the case for instance in Ulicny and Thalmann (2002).

Computational problems were also encountered during the calculation of spatial statistics on the InSiM generated data. SANET could only undertake calculations on up to 7,000 edges (SANET, 2009). Hence, SANET was unsuitable for analysis of the whole area. Consequently, whilst use of this software seemed the most promising with respect to the adopted analytical approach (network-based analysis), its full potential could not be explored.

The long processing time precludes utilisation of InSiM as a decision support tool during the incident response. Nevertheless, the model can be of an asset during specification of standard operating procedures or definition of response plans. In these instances longer processing time is not an issue. Even though the complexity of the road network challenged application of spatial statistics, alternative approaches were applied to assess the differences between the three InSiM configurations from different perspectives.

10.2.2 Lack of Real-life Data

Existing official and available documentation regarding response to CBRN incidents lacks information regarding the application of the national guidelines to local response. Therefore, from these materials it was not possible to identify problems and challenges that local responders face during an actual response operation. Hence, experienced incident commanders from the Nottinghamshire Fire and Rescue Service were contacted to gain further insight. Although only two officers actively contributed to the soft systems methodology analysis (Chapter 4), the collected information provided enough material for identification of areas where ABM could be actively used as a complementary decision support tool.

The lack of historical data of the required level of detail or quality depicting the reaction of people to CBRN explosions (or a similar type of incident) challenged the definition, validation and calibration of InSiM. A large number of existing geo-simulation models have overcome this problem by defining a set of often highly simplified assumptions on the system on which the model was developed (see Section 2.3.2.2). To demonstrate the limitations such decisions place on the data generated by the simulation, a significant part of this research was devoted to collection (Chapter 5), analysis (Chapter 6) and incorporation (Chapter 7) of empirical data in the geo-simulation models. The following steps were conducted to limit the assumptions about the real-life system to minimum:

- Two experimental studies were conducted to collect information regarding pedestrian response to a CBRN explosion. Since the intention was to obtain as broad a perspective of the situation as possible, the questions for the semi-structured interviews (SSI) as well as the discussions taking place during the photo-elicitation interviews (PEI) were intentionally kept at a high level of abstraction. This provided a possibility to also extract information for which the data were not originally collected. This was not anticipated prior to the research. Even though the extensive amount of collected material challenged its analysis, the quantity and diversity of the material proved to be a very big advantage. This was, for instance, demonstrated in the technique adopted for the definition of walkway categories; in particular the width of the walkway (see Section 7.2).
- The simulation environment was created using the national mapping digital dataset (OS Master Map). Since the original data did not provide the characteristics of the walkway width, additional data collection and processing needed to be conducted.

10.2.3 Constraints Put on Time and Resources

Several limitations were applied to development of InSiM due to the time and resource constraints. These limitations are:

- the restricted size and adopted sampling approach for the empirical research;

- the use of secondary data (collected for different purpose) for the definition of the walkway categories;
- the generalisation of the locations representing the following preferred destinations:
  - home (limited to four cardinal directions towards outskirts of the city),
  - open space (limited to two land marks located in the city centre);
- the use of a single factor for decision making of an agent (walkway width).

Notwithstanding the above limitations the development of InSiM demonstrated how real-life information can be implemented in the a geo-simulation model and what problems and issues still need to be addressed to make the models usable for the domain experts.

10.2.4 Generalisation of the Complex System

The application of soft systems methodology (SSM) identified that activities forming responses to a CBRN incident are complex, requiring a large team of experts and emergency personnel to accomplish. Narrowing down the focus to a description of the system related to placement of both inner and outer cordon zones around the affected area (INCORMS) still revealed an extensive number of activities. Implementation of such diverse information into InSiM would not be feasible since it would overwhelm the simulation and might conceal important details.

To keep the model transparent it was found necessary to implement only a limited part of INCORMS. The advantage of such an approach was that the particular sub-system could be better understood once separated. However, this could cause loss of connections with other sub-systems which in a real situation might have significant influence on its behaviour. For instance, the dispersion pattern of agents might be different if agents representing emergency officers, who can direct agents to safety, were implemented (as was for instance done by Shendarkar et al., 2006).

To limit the amount of information an agent has to process in each simulation step, only the most frequently referenced factor was implemented in InSiM (i.e. walkway width). Nevertheless, other factors have an influence on human decision in emergencies. Even though these were in InSiM omitted, they can be included in the agent's reasoning process as a part of the future research.

10.2.5 Representation of Complex Human Behaviour

InSiM does not represent group behaviour. This means that pedestrians are modelled as self-oriented individuals without any interest in adapting their behaviour to others. This corresponds with the information which was collected during the empirical research. This decision was made to limit the complexity of the information and focus more on the environmental factors since they have not been greatly explored in ABM research to date (see Section 2.3.2.3).

In particular, the presence of family or friends would have an influence on the behaviour depending on the position of the individual within the particular social group (Perry and Lindell, 2003; Mawson, 2005). Inclusion of such behaviour would require specification of agent's demographic and social characteristics to determine its position in the society. Such detailed information would challenge the implemented action selection mechanism (rule-based system) since the agent would have to be given an opportunity to observe the complex dynamic situation and consider its social responsibility to/dependency on others.

Despite these limitations the process adopted for development of InSiM illustrated how information regarding human behaviour can be collected, analysed, and successfully implemented into an agent-based model. The same process can be followed to extend the InSiM simulation capabilities of more complex human behaviours.

10.3 Evaluation of the Research Approach and Critique of the Methodology

The literature review identified that the majority of the assessed research projects concentrated on enriching the agent-based architecture with additional advanced features. This often resulted in highly complex computation in every simulation step. Although such research is very important, it is also necessary to focus on applicability of the current state-of-the-art for solving real-life problems. Only then the broader academic and non-academic community can appreciate what benefits such alternative modelling techniques offer. However, this was an aim of only a limited number of reviewed models (see Section 2.2.3).

This research focused on identifying and resolving issues that currently preclude the broader application of ABM for disaster management. The issues were grouped around five key aspects of the model development process:

- Understanding the Application Domain;
- Human Behaviour Representation & Parameterisation;
- Environment Representation & Sense of Space and Place;
- Reasoning Process;
- Results Analysis & Model Evaluation.

In the literature review each aspect was associated with a set of questions from which the competence and integrity of the reviewed models with respect to disaster management were assessed. To determine whether the methodology proposed in Chapter 3 resolved some of the identified issues the following sections focus on its evaluation through discussion organised around the same set of questions.

10.3.1 Understanding the Application Domain

10.3.1.1 Q1: Has initial investigation regarding understanding of the basic properties of the modelled system been conducted?

Yes. The application of SSM was revealed to be practical and useful for such investigation. Its several stage process enabled the researcher to gain an understanding of the system from the high level perspective (rich picture) to small-scale details (conceptual models). In addition, each of the steps provided different insights into the system introducing constant change in the point of focus allowing observation from different views.

The domain experts took active part in creating the rich picture which precluded any biases that would be caused by reinterpretation of the information due to misunderstanding. However, the results of processes involved in the remaining stages of SSM were based on the priorities and considerations of the researcher. For instance, selection and generalisation of activities by which the conceptual models were described was influenced by the researcher's interests. Hence the focus of the analysis was put on activities related to data and information processing for decision making rather than on the other INCORMS activities (as defined in the INCORMS conceptual model in Section 4.5) which are of an operational (e.g. *Cordon Placement*) or tactical nature (e.g. *Decide*). It was identified that during the decision making process the application of ABM can have the biggest impact and can help to overcome some of the INCORMS existing problems.

10.3.1.2 Q2: Have the system related problems and issues with respect to disaster management been identified?

Yes, but they depict the view of the Nottinghamshire Fire and Rescue Service. Identification of existing problems and issues forms part of SSM analysis (Stage 5: Comparing the conceptual model with the real world). Therefore, issues and problems related to INCORMS emerged naturally without the need of any additional technique. This appeared to be a big advantage of SSM. Moreover, the system was looked at from two distinct perspectives: real-world (represented by the rich picture) and ideal system (depicted by the conceptual model). This provided additional insight into the system by which deeper embedded problems and issues could be detected.

SSM was not used for detection of *all* existing problems at various levels of detail. The scale of the problems and their diversity was dictated by the focus of the research. As a consequence only problems and issues which could be resolved by ABM were discussed more closely. For illustration purposes, additional problems were referenced. These, however, only reflect knowledge of the domain gained during the course of this research and might therefore seem to domain experts as irrelevant.

10.3.1.3 Q3: Have the potential users of the model been consulted to specify their requirements of the model?

Yes, incident commanders from Nottinghamshire Fire and Rescue Service have been contacted to specify their requirements of the model. Due to the limited time which was allocated for the initial part of the model development process it was not possible to discuss the system at the same level with additional rescue services from different counties.

The outputs of the analysis were discussed with a representative from Nottinghamshire Constabulary to gain an independent opinion on the situation. Even though it was identified that the Police focus on different activities than Fire and Rescue Service, the SSM analysis were not expanded of this additional concerns, since sufficient information was obtained to identify how ABM can address some of the existing INCROMS problems. However, this finding clearly indicates the importance of communication between the response services and the implementation of a commonly agreed plan of actions which satisfies their diverse needs and priorities.

10.3.2 Human Behaviour Representation & Parameterisation

10.3.2.1 Q1: Has the behaviour of the agents been specified with respect to the behaviour of the real system entities the agents represent?

Yes, the behaviour of the agents is defined based on findings of the empirical research. Since the researcher does not have an appropriate qualification and experience to be able to interview real incident victims, the study participants were selected from the population of people who had no experienced such an event. This brings limitations to the representation of agents. Moreover, it could pose speculation whether the reported behaviour is realistic or whether instinct and the unanticipated nature of the explosion would trigger a completely different reaction.

10.3.2.2 Q2: Does the research reference the source which was consulted for definition of the agent's behaviour?

Due to the limited documentation of the response behaviour it was found necessary to collect data empirically in order to understand the behaviour of the system at the desired level of detail. The selection of the size and origin of the population sample was justified and its limitation discussed (see Section 5.7). To gain initial knowledge on the subject, human factors, psychology and sociology literature related to human behaviour in emergency situations was reviewed. The information obtained was used for construction of the experiments.

10.3.2.3 Q3: Has any additional research been conducted to obtain more information regarding the behaviour of the agents?

Yes, two sets of experimental studies were conducted: semi-structured interviews (SSI) and photo elicitation interviews (PEI). Each of the studies focused on collecting information about human behaviour from a different perspective. The application of qualitative data collection techniques enabled the collection of information which was not anticipated prior to the research (e.g. definition of the factors that influence human decisions during emergency situations). However, the complexity of the interview discussion challenged the analysis of the collected data. Moreover, it was also found that many participants contradicted themselves at different phases of the interview. Therefore, the interviewees were asked to clarify their claims through more specific questions.

Semantic problems related to different naming of the same concept or using the same expression with different meanings resulted in difficulties related to interpretation of the data. For instance, to some participants the concepts *main road* and *wide street* were perceived as synonyms while for others they had different meanings. Such problems were not anticipated during the course of the interview. Hence no questions that could have lead to further explanation of these concepts were asked. These problems were mitigated by reviewing the information within the context of the discussion. This was not obvious in the pilot studies due to their restricted size.

During the content analysis (CA) the definition of the categories by which the transcribed data were organised reflected the researcher's view on the data. The same transcripts could have been interpreted differently by different people.

The collections of photographs on which PEI were based limited the reasoning about evacuation route preference to locations depicted on each photograph. These photographs were taken by the researcher. They depict the locations that the researcher considered representative with respect to her own assumed reaction to a CBRN explosion. The experiments revealed that different people would react differently. Since every person considered different set of factors the photographs limited the context of the discussion. The limitation of the approach selected for creation of the photographic categories was only possible to identify once the data collected during the PEI were analysed. The level of the influence could not have been anticipated *a priory*.

Even though several problems were encountered during the empirical data collection and analysis, valuable insights into human response to CBRN explosion were obtained. Hence, this could be seen as a first step based on which additional qualitative or quantitative studies can be defined.

10.3.2.4 Q4: Does the parameterisation of the model correspond with the characteristics of the modelled system?

Yes, but due to data related problems it was not possible to validate InSiM and to assess to what degree the behaviour of agents corresponds with the behaviour of the real incident victims. However, steps towards capturing the situation as realistically as possible were taken, e.g. the extent of the explosion corresponds with parameters given by FEMA (2003); use of real geographic data to depict the simulation space; etc. Nevertheless the values of several parameters were based on assumptions. These are for instance communication distance, incident awareness radius, movement of unaware agents, etc. These remain to be addressed in the future research.

10.3.2.5 Q5: Do the attributes of the agents correspond with the entities they represent?

Yes, the findings of the empirical research were used to define these parameters. However, there is a trade off between the complexity regarding the number of parameters and their definition, and the scale of the model (number of agents, complexity of their behaviour and interaction, representation of the environment). Since the scale of the model has been found to be more important within the scope of this research, it was inevitable that the parameters and their values had to be limited. Therefore, only parameters that have been assumed to have the strongest influence on the behaviour as depicted in the conceptual model (Chapter 7) were implemented. Additional research needs to be done to clarify this selection.

In addition, it was found necessary to lower the complexity of the programming demands to speed up the model implementation. Since it was identified that in general demographic characteristics don't have any effects on the behaviour (at least within the population sample that was interviewed) the diversity of agents is represented purely by their navigation preference and the selection of their destination. This significantly simplified the demand on the agent's representation with respect to definition of its reasoning process.

10.3.3 Environment Representation & Sense of Space and Place

10.3.3.1 Q1: What format is used for the representation of the environment?

Based on the findings of the experimental studies the simulation space was represented as a geographically referenced network comprising of all navigable streets as depicted in OS Master Map (ITN layer). Each node depicts an important point on the road (crossroad, change in direction, etc.) and is represented by a set of coordinates that reflect its real location on the surface. The edges represent topological relations between these nodes and depict the road segments on which agents can navigate.

10.3.3.2 Q2: Has the selection of the specific environmental representation been sufficiently justified and properly explained?

The simulation space was generalised to represent geographical characteristics that have the strongest influence on human reasoning during an emergency situation. The extent of the generalisation was determined by the requirements put on the number of agents that needed to be included in the simulation. In addition, the classification of the environment into different walkway categories was based on information extracted from the experimental studies.

For the purposes of modelling the simulation space omits a large number of geographical features (e.g. buildings and parks). However, these features might have an influence on the final human behaviour which could result in alteration of the walking path towards the preferred destination. In order to detect the level of their influence, these features would need to be added to the simulation environment and their effects further studied. This is a recommendation for future research.

Definition of the preferred destinations in InSiM is highly simplified. As discussed, additional empirical data would need to be collected to identify which open space locations should be selected within the area of the use case scenario. These locations are likely to be city specific. Home destinations were in InSiM crudely approximated to four cardinal directions leading out of the city centre. Although this might not represent the situation accurately, it demonstrated the proportion of agents that would exit the city within the time under investigation.

10.3.3.3 Q3: Does the environment represent a real location? If yes, is the representation accurate for the selected scale of the geo-simulation?

In this research it was found imperative to use real geographic data for definition of the simulation environment. Therefore, it was possible to study the behaviour of a synthetic population with human-like attributes within a realistic road layout. This also made it possible to observe to what extent the road network and its characteristics influence the dispersion pattern.

As the ITN layer of the OS MasterMap contains the necessary data at a very high level of detail and quality it was used as a source for the specification of the simulation space.

Although the graphical representation of the road network is of a very high quality, the classification into the walkway categories was limited. Due to a lack of data regarding the walkway width, additional research needed to be conducted to collect such information. Several techniques were reviewed for how to achieve this but none of them was found to be sufficiently accurate (see Section 7.2.6.4). The classification of the road network was done indirectly, based on the information existing in the digital OS Master Map dataset. Since the width of the road varies along its length the classification is very rigid. Hence, its limitations need to be taken into account should the data be reused for different purposes.

10.3.3.4 Q4: Has the agent interaction with the environment been clearly specified?

Yes. The interaction is based on the information extracted from the experimental studies. The interaction is defined with use of a single factor which was the most commonly referenced.

The selection of the most appropriate path towards the preferred destination was affected by the set of weights associated with each walkway category. Even though the sensitivity analysis identified that the extent of the influence of the weights is not very significant it still alters the behaviour at the local level. The values of these weights were defined on the assumption that people would select a less preferable option if the "safer" route is significantly longer. This assumption needs further research to validate it.

10.3.3.5 Q5: Has the agent interaction with the environment been based on behaviour observed in the real-life system and the source of information properly referenced?

Yes. The agent's interaction with the environment is defined based on the findings of the empirical research. However, InSiM only reflects the behaviour of the population sample interviewed. The behaviour of the agents was limited to consideration of a single factor. These limitations must be taken into account should the information generated by analysis of the simulation outcomes be used for emergency planning.

10.3.4 Reasoning Process

10.3.4.1 Q1: What action selection technique has been used to represent the agent's reasoning process?

The rule-based system (RBS) was selected to represent agent's reasoning process.

10.3.4.2 Q2: Has the selected approach been adequately explained?

he algorithms by which an agent reasons in every simulation step was fully described succeeding to provide a clear insight into the mechanisms that generate the movement of agents in the simulation space. The structure of InSiM was formally described in accordance with the UML standard enabling software engineers to assess its qualities and deficiencies if they wish to advance its capabilities, reuse its architecture, or replicate the model.

10.3.4.3 Q3: Has the selected approach been justified?

The reasons for the selection of RBS were discussed in Section 7.3.3.1. Although RBS has been frequently used by researchers within the geographic domain (e.g. Batty et al., 2003; Castle, 2007; Mysore et al., 2006) it has some limitations. Extending RBS may cause numerous complications resulting in a loss of computational efficiency (Bryson, 2004). In particular, this approach becomes impracticable with an increasing number of situations that the agent needs to reason about. Moreover, the behavioural responses need to be mutually exclusive and the actions must be easy to map into situations. In its current implementation InSiM considers two distinct agent states AWARE and UNAWARE of the incident. Hence RBS appeared to be the right approach to use. Nevertheless, the action selection mechanism would have to be reevaluated and possibly replaced should InSiM be advanced to include more complex behaviour.

In order to identify to what degree use of other more complex reasoning processes would influence the final dispersion patterns, additional models depicting exactly the same situation would need to be designed and implemented.

10.3.5 Results Analysis and Model Evaluation

10.3.5.1 Q1: Have the results of the geo-simulation been analysed with respect to the purpose of the model?

Yes, the analyses of the results generated by the simulation were conducted with respect to the three model configurations. This was done to identify to what degree implementation of additional real-life information affects the dispersion pattern of the agents in the simulation space. Therefore, the analyses were undertaken by methods and techniques that could detect the change and determine its extent.

10.3.5.2 Q2: Has the adopted analytical approach been justified and adequately explained?

The clustered nature of the data caused complications which were not originally anticipated. It was assumed that application of goodness-of-fit statistical tests would be appropriate to demonstrate the significance of the differences between the dispersion patterns generated by the three different InSiM configurations. However, once initial tests were conducted it was identified that the impact of the clustering was much greater than anticipated. Nevertheless, the extent of the differences in the dispersion patterns were in addition assessed qualitatively by visual comparison of agents' density rasters (global perspective).

10.3.5.3 Q3: Does the research discuss the model's contribution and limitations?

The contributions and limitations of the proposed methodology are highlighted in this chapter by discussing problems and issues that were encountered during implementation of InSiM.

10.3.5.4 Q4: Has the model been properly validated, verified or calibrated?

Due to the lack of data representing the behaviour of people during a real-world CBRN incident full validation of InSiM was not possible. Therefore, additional evaluation with respect to accuracy of the represented behaviour would need to be undertaken before InSiM could be used operationally by domain experts.

InSiM was verified against the conceptual model to provide confidence in its behaviour. An extensive number of sensitivity analysis tests were conducted to depict sensitivity of InSiM to its key parameters. The adopted approach could only detect first order effects. Additional analysis would be needed to gain further insight into the model's logic.

10.4 Application of InSiM for Incident Site Management

Although InSiM was developed for the purpose of testing the proposed methodology it can still be used as a secondary source of information for incident commanders to assess effectiveness of the existing procedures related to cordon zones placement. As was discussed in Chapter 4, the inner cordon initially comprises a circle around the incident with a 400 m radius. By collecting data generated by InSiM it is possible to assess how the situation in the area of the inner cordon zone progresses through time. This assessment can help incident commanders to identify the time in which the inner cordon zone should be set up to provide for the most effective decontamination of the incident victims should the mass decontamination units be placed on the cordon's perimeter.

For this purpose the most advanced SAM configuration was tested on the Nottingham scenario. The locations of agents were collected every five minutes from the time of the explosion up to one hour. The distribution of the agents was converted into a density surface by the same technique as was used for the raster-based analysis of the simulation results in Section 9.4. The density surfaces are, together with the extent of the inner cordon, plotted in Figures 10.1, 10.2, and 10.3 where the time zero is depicted in image a) and one hour period in image m).

Visual analysis of the density rasters reveals that already in five minutes after the blast (Figure 10.1 b)) a clear pattern of agents congregating at the main roads leading from the incident area can be observed. In the same time higher density levels can be identified at the centrally located preferred destinations.

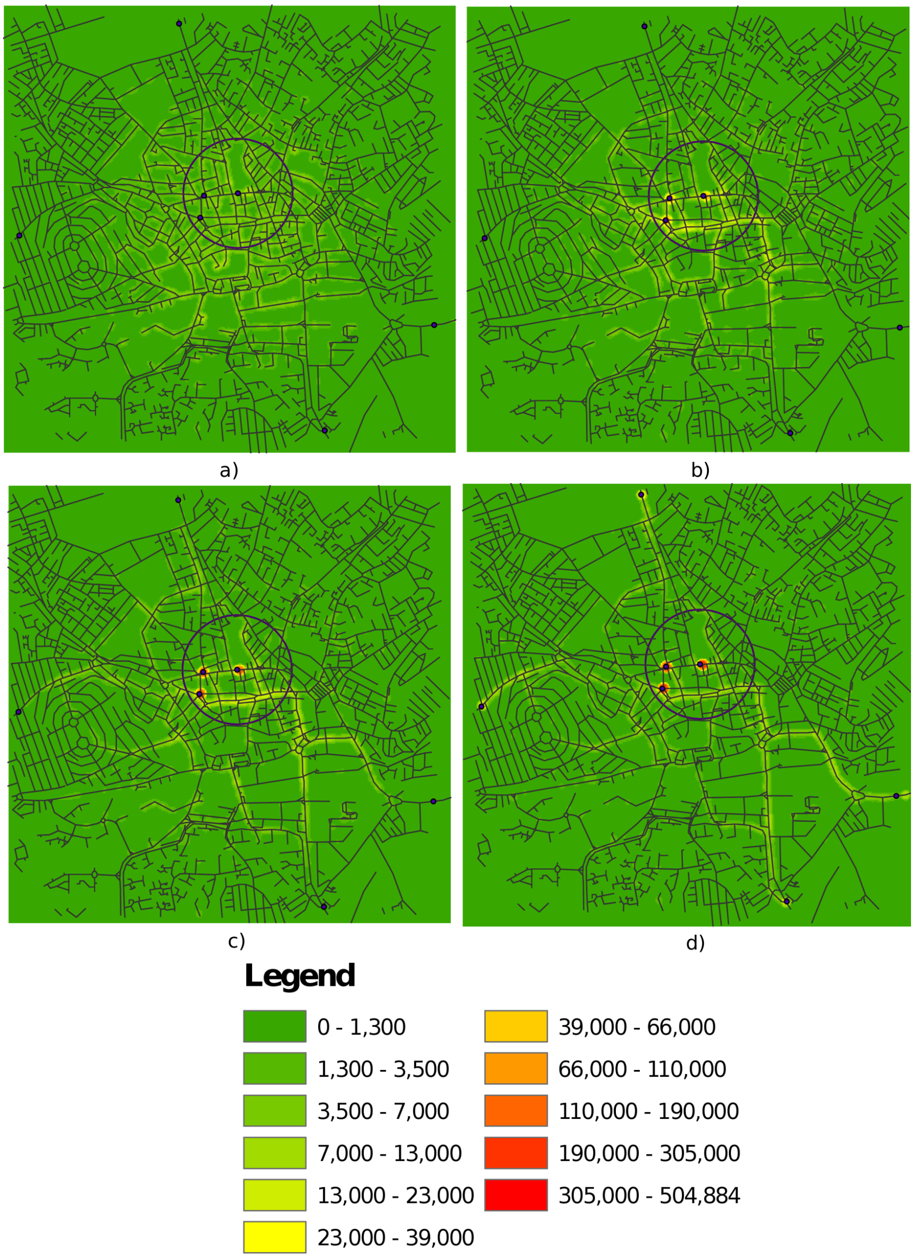

Figure 10.1: Distribution of agents with respect to inner cordon (0 min - 15 min).

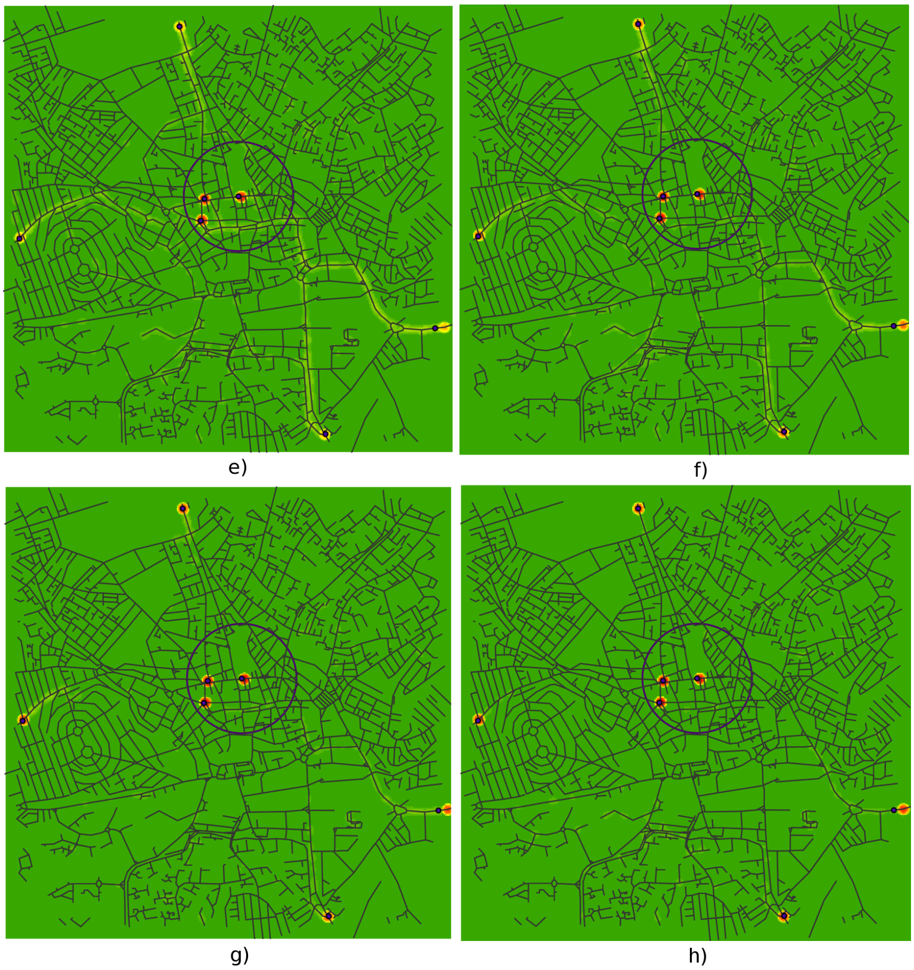

Figure 10.2: Distribution of agents with respect to inner cordon (20 min - 35 min).

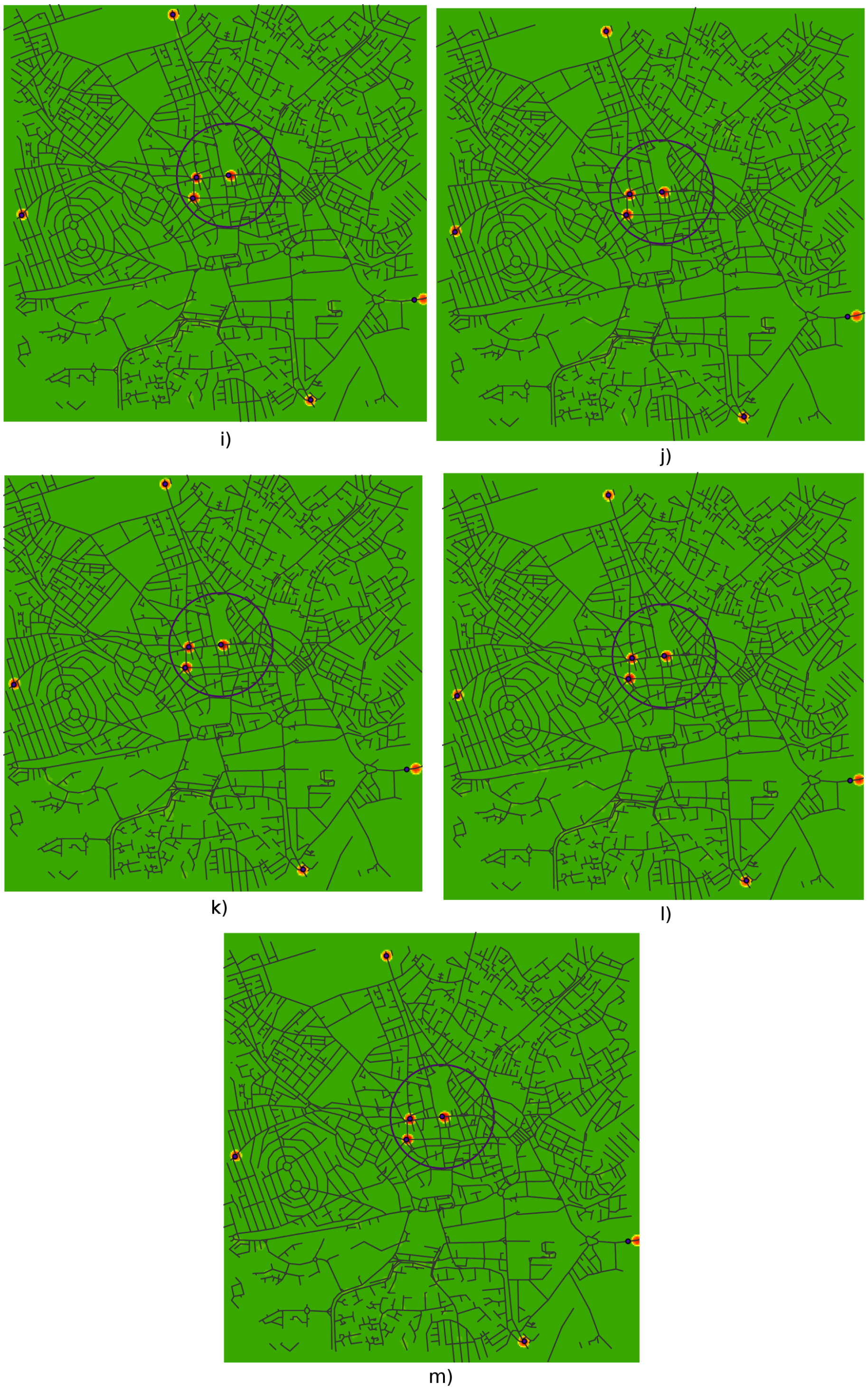

Figure 10.3: Distribution of agents with respect to inner cordon (40 min - 60 min).

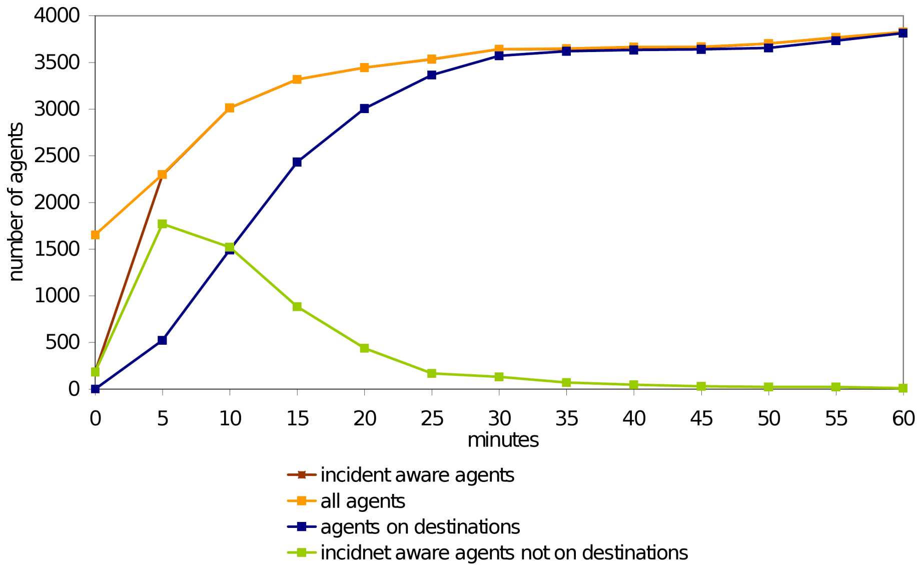

Figure 10.4: Graphical summary of agents within the inner cordon zone.

As the time passes, the number of agents in the inner cordon area, with exception of the destinations, rapidly decreases. Eventually, starting at 25 minutes time interval (Figure 10.2 f)), the situation within the inner cordon seems to reach equilibrium.

In addition to the density rasters the number of agents located in the 400 metre cordon zone was collected for each 5 minute time interval and plotted in Figure 10.4. To gain better understanding of the situation the graph depicts:

- agents that are aware of the incident,
- all agents located in the inner cordon zone,
- agents that have reached the three preferred destinations (open space areas and the incident) which are located within the inner cordon, and
- aware agents within the inner cordon which remain moving.

It can be observed that the number of aware agents rapidity increases from around 200 at the time of the blast to approximately 2,200 in the first five minutes. This reflects the rapid exchange of the information about the incident. In 10 minutes the number of agents that have reached the central destinations becomes equal to the number of aware agents that are heading towards home. As the time progresses the number of aware agents heading towards home decreases. The graph also shows that after the first 5 minutes all agents located within the cordon become aware of the incident. Although the density rasters show no visual difference after the 25 minute interval, the graph indicates some minor changes after this time period. The situation within the inner cordon zone stabilises approximately 35 minutes after the explosion.

These findings imply that a large proportion of the affected population would leave the area of the inner cordon zone during the first 35 minutes following the explosion. Moreover, only people that would be congregating at the incident area or open spaces which would be within 400 metres distance from the incident would remain. According to the findings of the experimental research (Chapter 6), this would be approximately 50 % of the incident victims.

This suggests that the currently adopted approach to cordon zone placement (INCORMS) is inadequate. In particular, setting up the mass decontamination units at the perimeter of the inner cordon zone would require resources to be in place early enough to direct people to the appropriate assembly points before they were too far from the incident area. These procedures should be put in place within 35 minutes after the blast. Alternatively, the mass decontamination units could be placed near the open space destinations or at the strategic exits from the city centre. Such an approach would provide the incident responders with more time to act.

10.5 Contextualisation of Research Findings

The overall aim of this research was to advance the state-of-the-art of agent-based simulation to produce richer models that can realistically represent real-life disaster management systems. The main points emerging from the research findings and their implications for the scientific and the application domain are discussed in the following paragraphs.

One of the most significant findings presented in this thesis is the identification of practical and conceptual issues related to the development of agent-based models for supporting the resolution of real-life problems. These issues were identified from the review of currently published scientific literature and from experience gained by developing an operational geo-simulation model. Even though some research projects addressing computational issues have been conducted, conceptual issues related to generalisation of complex real-life systems into a simulation model has remained an unexplored area of ABM research. This research attempted to fill this void.

This research focused on resolving issues and problems related to incorporation of real-life information into the geo-simulation models. A fully functional model (InSiM) was developed to demonstrate how utilisation of such information could expand applicability of the developed models which are mostly created as prototypes rather than fully operational tools. The collection, analysis and subsequent application of real-life information was demonstrated as part of the model development process. The process faced several challenges which could not be easily resolved with the resources available. Nevertheless, the work undertaken served as the first step for identifying and exploring ideas for more focused research.

In order to address the research question it was found necessary to apply methods and techniques from other scientific domains. This approach expanded the research possibilities allowing exploration of the development process from several different perspectives and providing deeper understanding of the existing issues and problems. As a consequence it was possible to identify the potential for research from various scientific disciplines (computer science, geography, social science, human factors, GIScience, etc.) to advance this simulation approach.

The effort put into collection and analysis of the real-life information and its subsequent use in development of an operational model demonstrate the potential of ABM in disaster management. Nevertheless, the computational complexity of the algorithms preclude the simulation from running in real-time. This problem could be overcome by running the model on more powerful machine or by parallelly distributing the processing to several computers. However, such high-specification technology is not likely to be invested in by the response organisations unless a clear return of the invested resources can be anticipated. Therefore, it is important to communicate with the domain experts and demonstrate the benefits ABM can bring.

10.6 Summary

This chapter discussed the proposed methodology through evaluation of its application for development of InSiM. It highlighted advantages and achievements that have been accomplished by a number of methods and techniques adopted from different scientific disciplines. Limitations and constraints that had not been anticipated at the initial stage of the research were discussed.

The chapter illustrated the complexity and diversity of problems and issues that utilisation of real-life data and domain knowledge bring to the development of agent-based models for disaster management. It argued the potential of agent-based technology in disaster management as an alternative source of data for incident commanders and policy planners. It also identified that a number of problems still need to be resolved before it can be exploited for every day use.

Chapter 11

Summary, Conclusions and Further Research

11.1 Introduction

The originality and novelty of this research lies in the investigation of issues and problems that preclude wider utilisation of ABM in disaster management. This is a perspective that has not been greatly explored within the disaster management domain and has received only limited interest in others. This research focuses on enhancing geo-simulation models with real-life information. It was identified that such information can be an asset across the whole model development process. To date, only limited research has been conducted on identifying and resolving the problems and issues that use of real-life information encounters. A methodology which demonstrates how real-life information can be collected, analysed and incorporated into the geo-simulation models is proposed, tested, and evaluated.

Section 11.2 summarises this research by discussing its main findings around the research objectives stated in Chapter 1. Conclusions emerging from the Discussion Chapter 10 are presented in Section 11.3. Recommendations for future research are provided in Section 11.4.

11.2 Summary of the Main Findings

The overall aim of this research was to advance state-of-the-art of ABM and to produce richer models that can more realistically represent real-life disaster management systems. In order to accomplish this aim five research objectives were formulated. The following paragraphs demonstrate how successful this research was with respect to meeting these objectives.

Objective1: Review and critically discuss current state-of-the-art agent-based modelling in disaster management with respect to its suitability for simulating real-life domain specific systems.

In order to identify current state-of-the-art in ABM, 35 geo-simulation models developed in the last two decades were assessed from several perspectives (Chapter 2). The potential of the models within the disaster management domain was discussed. It was identified that the main interest, in the recently published research, was aimed at developing models that represent evacuation of people from enclosed areas or open spaces. This would suggest that the research focus has been predominantly on representation of real-life situations to mitigate consequences of incidents. However, further analysis revealed that the majority of these models were developed to test the robustness and extensibility of this simulation approach. This indicates that disaster management for many researchers is seen as an interesting testing environment rather than a domain to which ABM could be applied to generate information and knowledge about a specific system. This finding was extremely valuable since it revealed a gap in the existing research focus.

Objective 2: Identify problems and issues that are connected with development of such models and summarise them in a transparent form.

An additional key finding of Chapter 2 was that development of an agent-based model is connected with a large number of problems and issues. Based on review of five scientific publications that discussed suggestions, methodological steps and challenges posed on ABM, the emerging issues and problems were organised into five aspects:

- Understanding the Application Domain,
- Human Behaviour Representation & Parameterisation,
- Environment Representation & Sense of Space and Place,
- Reasoning Process,
- Results Analysis & Model Evaluation.

To gain a common view the findings of the five publications were organised with respect to the above aspects. It was discovered that none of the researchers discussed the full range of aspects with respect to the model development. From this discovery two conclusions can be drawn. Firstly, the complexity and diversity of the considerations related to development of geo-simulation models representing real-life systems challenge the definition of a single, generally accepted framework, that could guide their implementation. Secondly, the current research focuses mainly on a specific area within which the emerging issues are identified and addressed. However, only limited interest is given to reflection on how these improvements affect the overall functionality and reliability of the model.

To obtain a deeper insight into this matter the 35 selected models were assessed once more. In this instance the focus was put on detecting how the identified aspects had been considered during the model development process. This revealed a number of patterns of which, perhaps, the most significant was the lack of utilisation of real-life data and domain knowledge for definitions of the model. The absence of this information indicated that although the models meant to simulate emergency of real-life systems (e.g. evacuation from an enclosure, work of response units, etc.) the behaviour of the agents did not correspond with the behaviour of the real-life entities they represented. Moreover, the agent definitions were mostly based on simplified assumptions of the researcher about the system.

It was concluded that this is due to the absence of time and resources spent on conducting additional studies by which the behaviour can be identified. Since most of the current research is of a computational nature (as highlighted in the findings related to Objective 1), this would require the application of qualitative or quantitative data collection techniques (e.g. interviews, questionnaires, work observations, etc.) that highly oriented technology researchers are often not familiar with.

Objective 3: Propose an advanced methodology for development of domain specific agent-based models which focuses on addressing the identified problems and issues.

The findings that were obtained from addressing the previous two objectives provided the foundation for defining a methodology for the development of agent-based models for purposes of disaster management (Chapter 3). The analysis of the literature revealed that ABM can simulate diverse systems and situations within the disaster management domain. This implies that if the methodology was to be generally applicable, it had to be defined at the appropriate level of abstraction.

To provide an example of how this methodology can be applied, possible methods related to each development step were proposed. It was identified that the selection of the specific techniques is directed by the nature of the system that is to be modelled and the form of the simulation results.

Due to the complexity and diversity of the real-life information, it was found necessary to incorporate it into the methodology in three separate stages. In the initial development step the focus was put on understanding the fundamental structure of the modelled system as it is recognised by the policy planners and incident responders (Chapter 4). This enabled the identification of areas where ABM could be of value.

Secondly, the real-life information was considered when defining behaviour of the interacting agents (Chapters 5 and 6). In this instance the emphasis was put on ensuring the that reaction of an agent to specific stimuli corresponds, within a desired level of accuracy, with the behaviour of the system entity the agent represents.

Finally, in order to study behaviour of the synthetic population of agents in realistic environments the simulation space needed to be defined using real geographical data. Hence, during the development of the conceptual model (Chapter 7) significant effort was devoted to generalisation of the complex geographic space into an appropriate format.

Objective 4: Test and evaluate the methodology by developing an agent-based model through following each of its suggested steps.

The proposed methodology was tested through development of an agent-based model (InSiM) that represents reaction of pedestrians to a CBRN back-pack size explosion in a city centre. Each methodological step was followed through Chapters 4 to 9.

On of the key findings regarding the collection of the real-life information with respect to both domain knowledge and the behaviour of the pedestrians was the lack of freely accessible data and documentation at the desired level of detail. Hence, it was found necessary to conduct empirical studies to obtain the information needed. The domain related information was collected through application of the soft systems methodology reported in Chapter 4. Within Chapter 5 two experimental studies that were carried out to collect data on human reaction to CBRN incidents were reported.

However, due to the complex nature of the system it was found necessary to introduce some limitations. The processes related to the incident response were reviewed only from the perspective of the local fire and rescue service and the experimental studies were conducted only with participants who have not experienced such an event. Therefore, the data only reflect a view of a single response organisation and the reported human behaviour is based on assumptions people have about their reactions in such an emergency situation. Hence, the information extracted from the data cannot be generalised. Nevertheless, these steps were extremely important because the collected data served as a source of information for consequent chapters.

The data were analysed in Chapters 6 and 7. It was identified that the most common reaction to a CBRN explosion would be evacuation towards safer places such as home or open spaces where people can await help from the response personnel. However, it was also identified that some people would walk towards the incident due to curiosity or in order to help others. In addition, it was detected that the most frequently referenced factor influencing human reaction in such a situation appears to be the width of the road.

During design and implementation of InSiM (Chapters 7 and 8) further analyses were conducted to obtain additional information needed to define the structure of the model. Due to the qualitative nature of the data and the small size of the population sample, which was not selected randomly, a qualitative approach to the analysis was adopted. However, this brought about additional problems when the findings needed to be quantified before they were incorporated into InSiM. These problems were probably most apparent during generalisation of the geographical space into the simulation environment, and when the synthetic population of agents was allocated to the various preference categories (e.g. target destinations, navigation options, etc.).

In order to assess the importance of incorporating real-life information into agent-based models three configurations of InSiM were developed. Each configuration applied the real-life information at a different level of complexity. A number of unexpected complications were encountered when the results were examined by comparison of the agents' distributions generated by the different InSiM configurations in Chapter 9. Goodness-of-fit tests were applied to evaluate whether the differences were statistically significant. However, the results of the tests were heavily affected by the clustered nature of the data caused by the constraints put on agents' movement (only on a road network). Therefore, alternative approaches were adopted by postprocessing the data to a more suitable format or by assessing the emerging patterns qualitatively. The comparisons revealed global and local differences between the dispersion patterns. This suggests that the use of real-life information affects the outcomes of the simulation. Hence its incorporation should not be omitted when developing a geo-simulation model for disaster management purposes.

InSiM validation, verification and calibration reported in the second part of Chapter 9 was affected by the limitations of the collected data and complications encountered during the analysis of the simulation outcomes. The validation was only possible with respect to the data collected by the empirical research. Hence, InSiM represents the situation as it was reported by the selected population sample. Special attention was put on calibration of InSiM by performing a sensitivity analysis of its key parameters. However, minimalistic approach, where only a single parameter was assessed at time, was adopted. Nevertheless, it was identified that the dispersion patterns of agents are highly sensitive to the locations of the destinations, as well as to the layout of the simulation space and its characteristics, and the distribution of the agents' preferences.

Objective 5: Analyse outcomes and findings from objectives 1-4 and make appropriate recommendations in form of directions for future research.

It was identified that it would not be feasible to define a detailed development process which could be applied without any further adjustments as a standard for implementation of agent-based models for purposes of disaster management. This is due to the diversity of systems which the models can represent. However, it was found sensible to propose a methodology at a higher level of abstraction, which could provide generic guidelines on how real-life information can be incorporated into the model development process. These generic guidelines could be further adjusted according to the needs of the application domain. Recommendations for future research are discussed in Section 11.4.

11.3 Research Conclusions

- The development of InSiM demonstrated that incorporation of real-life information into geo-simulation models is a tedious process requiring high effort and use of a considerable amount or resources. Nevertheless, the emerging product has a number of limitations since several challenges discovered during the development process remained unaddressed. These are mostly related to generalisation of the complex real-life system into the computational model.

- Standard personal computers do not fulfil the computational demands of the geo-simulation models. Limited computational power constraints the level of complexity of the real-life system representation and analysis of the generated data. This could be overcome by utilisation of more powerful computers or by distributing the computation to several parrallelly connected machines. It is clear that the domain experts need to be presented with the benefits of the geo-simulation models before they invest into these high-specification systems. At this point in time, ABM faces a number of limitations which need to be resolved before its potential can be fully appreciated by the disaster management experts.

- This research demonstrated that the use of techniques and methods from several scientific disciplines can support the model development process. However, a number of problems and issues connected with their application were identified. These can be addressed by a holistic approach where researchers with different scientific backgrounds cooperate and collaborate on their resolving.

11.4 Suggestions for Further Research

In the following paragraphs areas for potential future investigations are highlighted. The section is organised in the same manner as the discussion of the main research achievements and limitations in Chapter 10.

11.4.1 Understanding the Application Domain

Further research should be conducted to enrich the description of INCORMS of views from other response services such as the police, ambulance, etc. It would then be possible to obtain an understanding of the system at a much deeper level. This would provide opportunities for discovering additional areas where ABM could be applied.

In order to identify whether there is a potential for models such as InSiM to become a standard tool within disaster mitigation units or response command centres it is necessary to carry out the soft systems analysis also with commanders from other UK counties to obtain a single and generally valid description of INCORMS. Such analysis could also reveal whether the implementations of the national guidelines into local response procedures are conducted differently in every county. This would provide evidence that appropriate steps would need to be taken to facilitate co-operation of disaster management teams across the whole country and possibly internationally.

11.4.2 Human Behaviour Representation & Parameterisation

There is a vast potential for improvements with respect to human behaviour representation and parameterisation within InSiM. The model definitions in this thesis have been limited to data which can not be assumed to be representative of the whole population. Hence, additional data would need to be collected to gain further insight into human reaction to the CBRN incident. This could be done by implementing more focused questionnaires based on the current findings. Alternatively, other qualitative methods such as analysis of existing CCTV footage of similar types of emergencies or interviews with incident witnesses could provide a reliable source of information.

In its current version InSiM incorporates a single factor that influences an agent's movement in the simulation space. A logical next step would be to expand the agent's reasoning to additional factors that have been identified by the analysis of the behavioural data. In InSiM the social and family bonds have been omitted. However, the participants indicated that presence of a person that was close to them (in an emotional context) would have an influence on their resulting behaviour. Therefore, further research of this matter, and consequently implementation of its findings into InSiM, would be valuable.

11.4.3 Environment Representation & Sense of Space and Place

In InSiM the complex geographic space has been represented as a geo-referenced network. Extending InSiM to support switching between different forms of simulation space would enable the study of to what extent representation and generalisation of the environment affects the simulation outputs.

There is a potential for expanding agents' spatial behaviour of more complex capabilities. Currently, it is assumed that all agents are familiar with every street in the city centre area. This is often not the case in real-life situations. Therefore, enhancing local knowledge or learning the environment as the simulation progresses could result in more realistic movements.

It was identified that there is a lack of suitable environmental data that could reflect the characteristics of the influential factors. In particular, problems were encountered when the road network was classified into the walkway categories. Therefore, additional research that could facilitate definition of the spatial attributes (in this instance walkway categories) and the classification of the environmental data with respect to these categories would be desirable.

11.4.4 Reasoning Process

In InSiM the reasoning process of an agent is represented by a rule-based system. A number of alternative reasoning mechanisms were reviewed before this selection was made. An interesting step forward would be to test several different reasoning processes (e.g. FSM, BDI, etc.) and evaluate to what extent they affect the behaviour of the model. It would then be possible to assess whether the reasoning process has a significant impact on the results of the simulation.

11.4.5 Results Analysis & Model Evaluation

To overcome further problems with analysis of the simulation outcomes adjustments to applied statistical techniques can be made to better suit the clustered nature of the data. This would for instance involve additional experimentation with spatial goodness-of-fit tests (e.g. the nearest neighbourhood G-function) on network environments. Alternatively, additional techniques could be tested such as Hotelling's t-square statistic that is generalisation of Student's t-test for multivariate hypotheses (Johnson and Wichern, 2007).

Another area that has great potential for development within ABM research is the method by which sensitivity analysis can be conducted. The use of algorithms that could autonomously detect strong correlations between several parameters and identify how such relationships affect the overall model behaviour could provide a better overview of the model sensitivity. Additional research can be conducted to investigate techniques for validation of agent-based models. In particular, alternative validation processes should be developed for models such as InSiM which simulate systems for which real-life data at the desired level of quality are difficult to obtain.

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Appendices

Appendix A

Root Definitions and CATWOE Analysis of INCROMS Sub-systems

Table A.1: Root definitions of INCROMS sub-systems.

Obtain Resources	*An incident commanders' owned system, operated by incident commanders, administrative and technical staff, and command and control personnel, to meet the need for resources, in order to assure that sufficient and fully functional resources are available at the local and regional level, while considering the insufficient amount and restricted availability of reserves and lack of trained personnel.*
Gather Knowledge	*An incident commanders' owned system, operated by incident commanders, administrative and technical staff, and command and control personnel, to meet the need for knowledge, in order to empower correct decisions, while considering issues with knowledge transparency and documentation, not existing record of the knowledge and contradicting, unstable or lost knowledge.*
Collate Information	*An incident commanders' owned system, operated by administrative and technical staff, to acquire relevant high quality information, in order to support decision making process, while considering interoperability issues, restricted access, ethical issues, communication difficulties, existence of incorrect or contradicting information and problems with uncertainty.*
Protect	*A command and control personnel owned system, operated by emergency response personnel, to fulfil demand of knowing what to protect and how, in order to provide timely and appropriate guidance for protection of majority of the system customers, while considering the behaviour of general public and victims, possible misunderstanding of the nature of the event, confusion in recognition of what is meant to be protected, insufficient guidelines, rules and regulations.*
Decide	*An incident commanders' owned and operated system, to determine the location of cordons, in order to take control over the situation and organise the response operation, while considering time constraints, quality and quantity of information, stress, high workload, experience and local knowledge of the response personnel, current state of the incident, different priorities, negotiations between ideal and realistic outcomes and availability of resources.*

Continued on Next Page...

Establish Working Environment	*A command and control personnel owned system, operated by command and control personnel and emergency response personnel, to provide safe and sufficient working environment, in order to facilitate the work of emergency response personnel, provide efficient and effective response, set necessary equipment and facilities into right place and reduce risks of danger for the response personnel, while considering layout of the environment, accessibility, weather conditions, indirect hazards from the incident e.g. debris, unstable buildings, block roads, etc.*
Cordon Placement	*A command and control personnel owned system, operated by emergency response personnel, to place the cordons in the right location, in order to arrange protection, secure the working environment, contain the incident and manage the situation, while considering lack of physical resources and trained personnel, accessibility of the incident site and its surroundings, uncooperative behaviour of general public and victims, vandalism, relocation of the cordons due to secondary explosion or additional threats.*
Monitor and Evaluate	*An incident commanders' owned system, operated by incident commanders, emergency response personnel, and command and control personnel, to meet the need for monitoring and evaluation of the processes involved in the INCORM system, in order to improve its progress, speed up the decision making process, identify issues and problems with currently adopted process, while considering problems related to unstructured or missing information provided, different criteria used by different response organisations, operational constraints, and lack of personnel at the regularly planned breathings.*

Table A.2: CATWOE analysis of INCROMS sub-systems.

	Obtain Resources
C	incident commanders
A	incident commanders, administrative and technical staff, command and control personnel
T	need for resources ⇒ need met
W	assurance that sufficient resources which are in fully functional state are available at the local and regional level will guarantee that their distribution can be allocated as required
O	incident commanders
E	lack of trained personnel; insufficient amount of resources; restricted availability of reserves
	Gather Knowledge
C	incident commanders
A	incident commanders, administrative and technical staff, command and control personnel
T	need for knowledge ⇒ need met
W	knowledge of sufficient quality and quantity to empower correct depictions

Continued on Next Page…

O	incident commanders
E	knowledge is not transparent; knowledge is not recorded and documented; unstable or lost knowledge; contradictory knowledge
	Collate Information
C	incident commanders
A	administrative and technical staff
T	unprocessed available information ⇒ relevant high quality information acquired
W	sufficient quality and quantity of information support decision making processes under the assumptions that all information needed is available
O	incident commanders
E	interoperability issues; restricted access; ethical issues; communication difficulties; existence of incorrect or contradicting information; problems with uncertainty
	Protect
C	incident commanders
A	emergency response personnel
T	demand of knowing what to protect and how ⇒ list of items to protect along with actions and activities how to achieve desired protection
W	can improve progress of the response operation; reduce number of casualties and losses
O	command and control personnel
E	unexpected behaviour of victims and general public; possible misunderstanding of the nature of the event; confusion in recognition of what is meant to be protected; insufficient guidelines, rules and regulations
	Decide
C	emergency response personnel
A	incident commanders
T	the most appropriate location of cordons unknown ⇒ location of cordons determined
W	turning chaos into an ordered response operation, taking control of the situation
O	incident commanders
E	time constraints; quality and quantity of information; high stress factors; high workload; experience and local knowledge of the response personnel; current state of the incident; different priorities; negotiations between ideal and realistic outcomes; availability of resources
	Establish Working Environment
C	emergency response personnel, HM coroner, governmental agencies, private sector organisations, voluntary sector
A	command and control personnel, emergency response personnel
T	requirement for safe and sufficient working environment ⇒ working environment provided
W	facilitate the work of emergency response personnel; provide efficient and effective response; correct positioning of equipment and facilities; reduce risk of danger for the response personnel
O	command and control personnel

Continued on Next Page…

E	layout of the environment; accessibility; weather conditions; indirect hazards from the incident; debris, unstable buildings; blocked roads, etc.
Cordon Placement	
C	incident commanders
A	emergency response personnel
T	demand of knowing what to protect and how ⇒ list of items to protect along with actions and activities how to achieve desired protection
W	can improve progress of the response operation; reduce number of casualties and losses
O	command and control personnel
E	uncooperative behaviour of victims and general public; vandalism; relocation of the cordons due to secondary explosion or additional threats
Monitor and Evaluate	
C	incident commanders
A	incident commanders, emergency response personnel, command and control personnel
T	need for monitoring and evaluation of the processes ⇒ need met
W	can improve progress of the response operation; can speed up the decision making process; can reveal problems and issues with the currently adopted process
O	incident commanders
E	needed information is not provided by the personnel; information is not structured; different criteria used by different response organisations; constraints determined by standard operating procedures and regulations; missing personnel at the regularly planned breathings

Appendix B

Conceptual Models of INCROMS Sub-systems

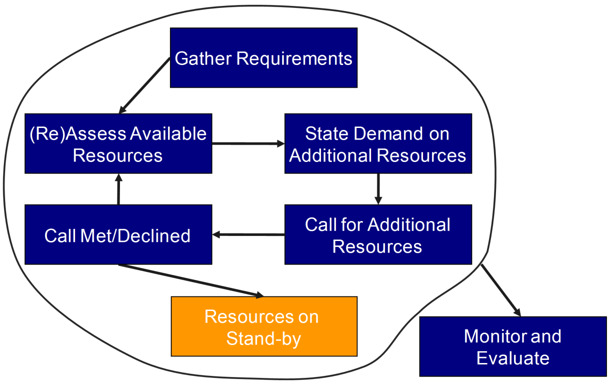


Figure B.1: Conceptual model representing sub-system of *Obtain Resources*.

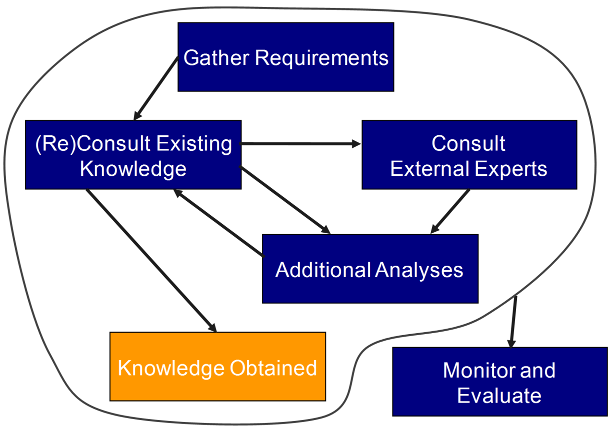


Figure B.2: Conceptual model representing sub-system of *Gather Knowledge*.

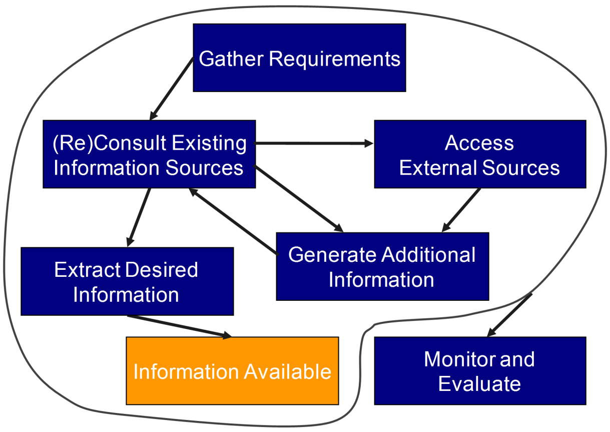


Figure B.3: Conceptual model representing sub-system of *Collate Information*.

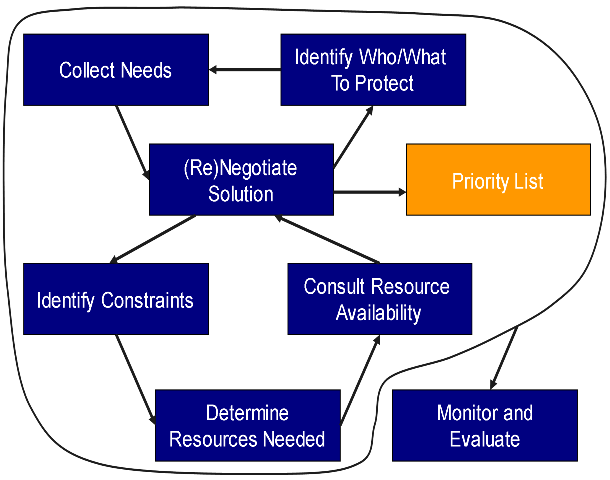


Figure B.4: Conceptual model representing sub-system of *Protect*.

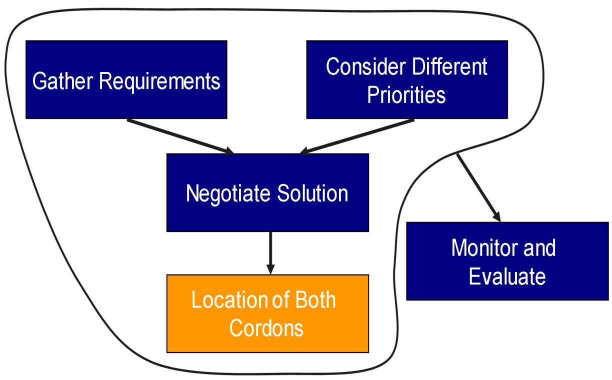


Figure B.5: Conceptual model representing sub-system of *Decide*.

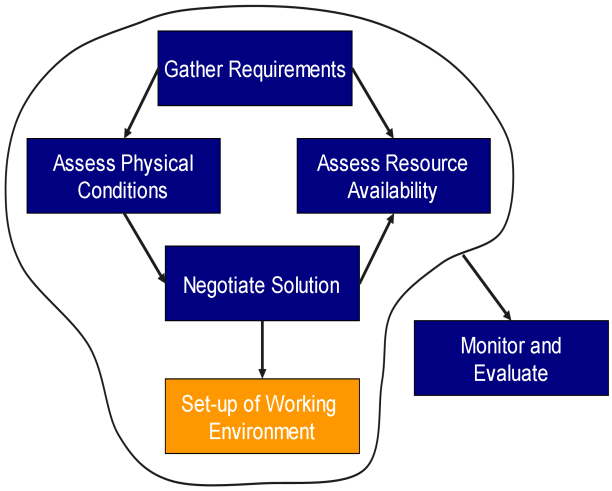


Figure B.6: Conceptual model representing sub-system of *Establish Working Environment*.

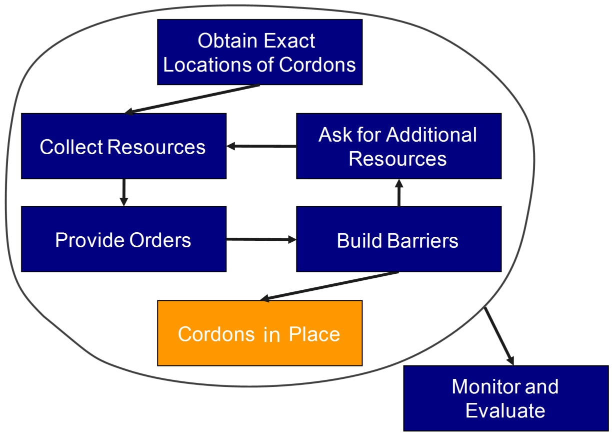


Figure B.7: Conceptual model representing sub-system of *Cordon Placement*.

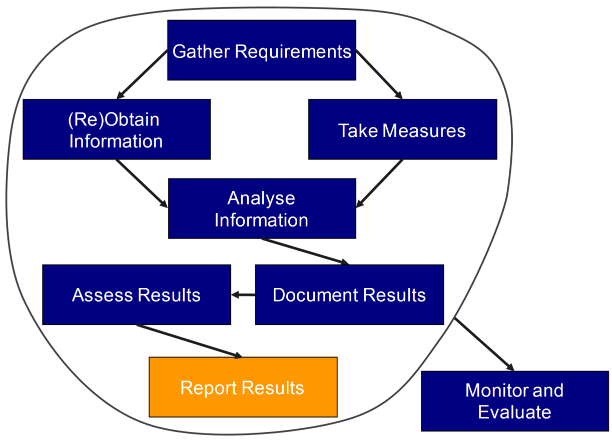


Figure B.8: Conceptual model representing sub-system of *Monitor and Evaluate*.

Appendix C

Questionnaire

Investigation of how people act in an emergency situation

The aim of this survey is to identify how people move around after an explosion in a city centre. This study will also identify reasons which influence people to move in the way that they do.

Survey number: ☐☐☐

A) Personal Information:

1) What is your gender?
(please tick appropriate box)

Female ☐ Male ☐

2) What is your age? ______
(To nearest year)

3) What is your occupation?

____

B) Familiarity with the study area:

4) Do you live in Nottingham?

Yes ☐ No ☐

If yes, for how many years? __________
(to nearest year)

5) Do you live in Leicester?

Yes ☐ No ☐

If yes, for how many years? _________
(to nearest year)

6) Please indicate how much are you familiar with Nottingham city centre?
(Please tick appropriate box on scale)

Very familiar ☐ ☐ ☐ ☐ ☐ ☐ Not at all familiar

7) Please indicate how much are you familiar with Leicester city centre?
(Please tick appropriate box on scale)

Very familiar ☐ ☐ ☐ ☐ ☐ ☐ Not at all familiar

8) Can you identify the area on each of the following pictures?

	Yes	No		Yes	No
Picture 1:	☐	☐	Picture 4:	☐	☐
Picture 2:	☐	☐	Picture 5:	☐	☐
Picture 3:	☐	☐	Picture 6:	☐	☐

Appendix D

Informed Consent

Centre for Geospatial Science

The University of Nottingham

Informed Consent

Recorded Discussion

- I understand the objectives of the discussion.
- I understand that I may withdraw from the discussion at any time without explanation.
- I understand that I will not be identified by name in any analysis of the discussion data.
- I agree that the discussion may be recorded on tape and then transcribed for analysis.

Signed:

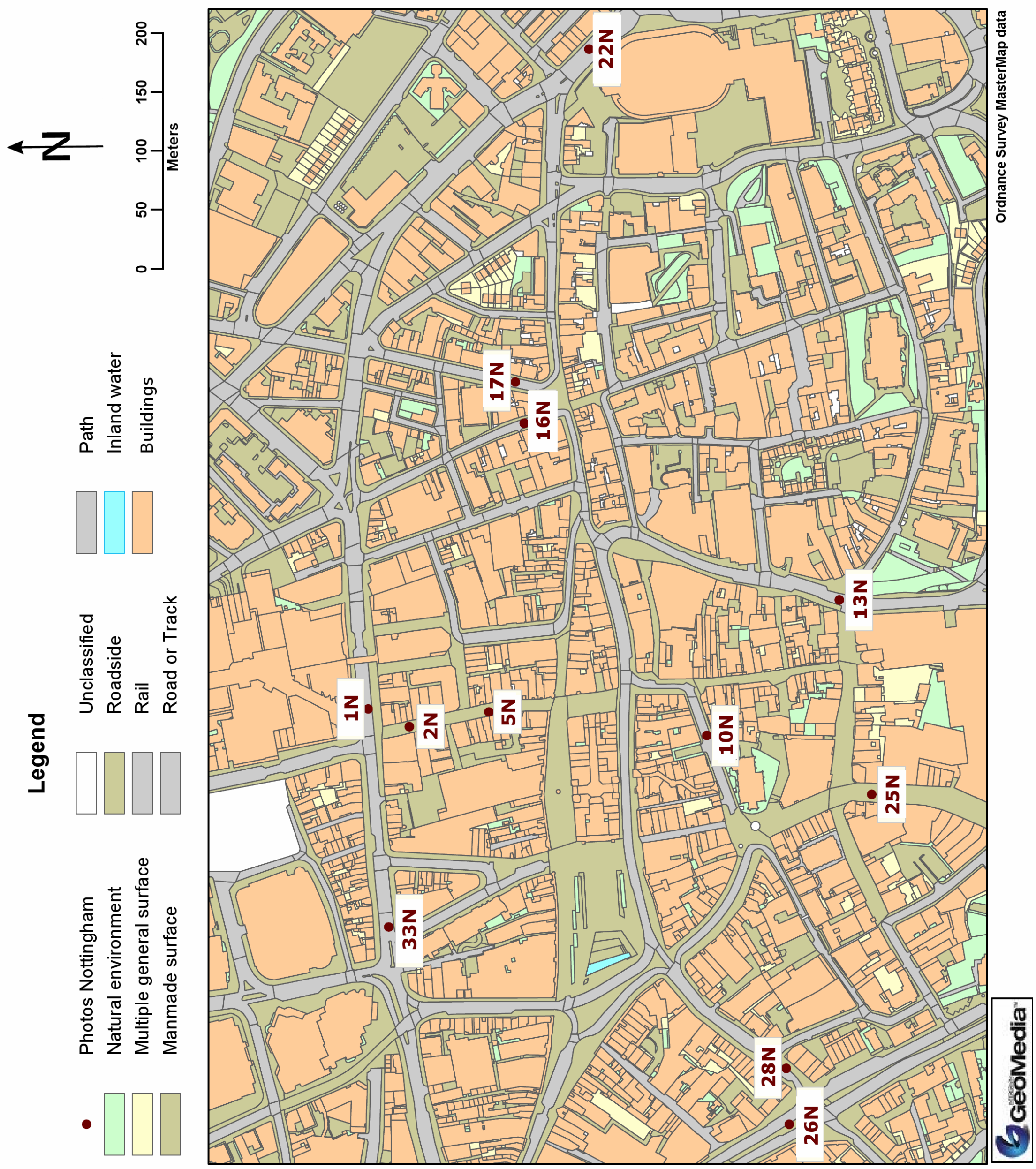
____

Print Name:

____

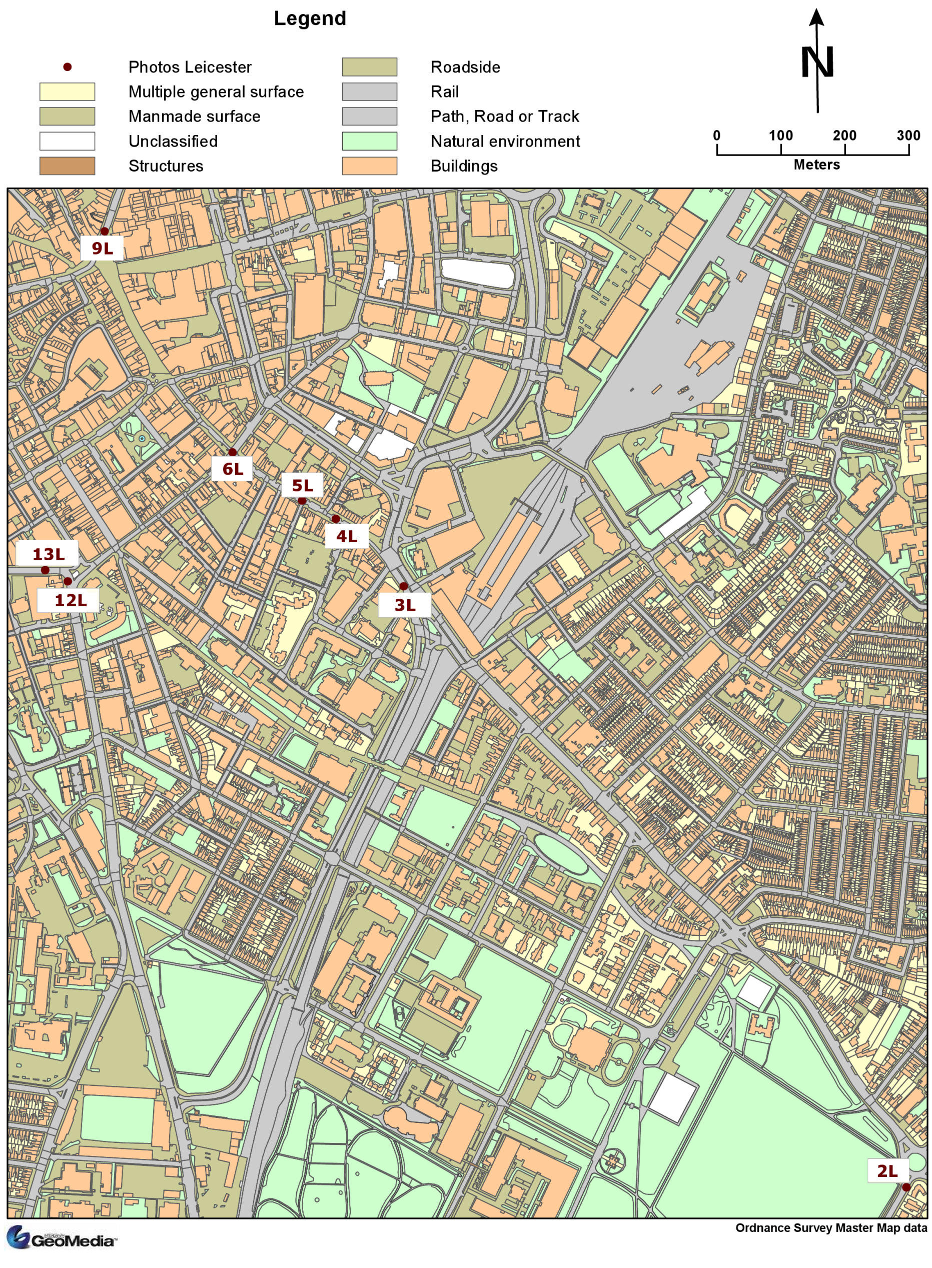
Appendix E

Location of Photographs in Nottingham



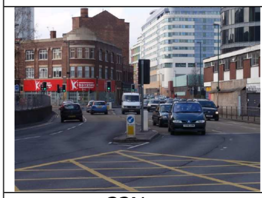
Appendix F

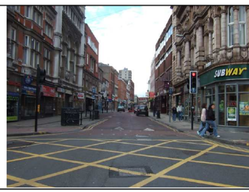
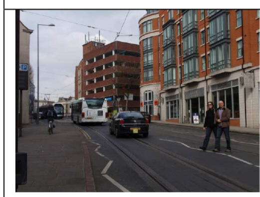
Locations of Photographs in Leicester



Appendix G

Photographic Categories for PEI

Dual carriageway		
		
22N	26N	3L
Pedestrianised "high street"		
		
2N	5N	25N
Main road A		
		
1N	33N	12L
		
13L		

Main road B		
		
2L		
Side street		
		
16N	17N	5L
Common street A		
		
10N	4L	6L
Common street B		
		
13N	28N	9L

Appendix H

Factors: Analysis of SSI Dataset

	Road width
P4	*"I would navigate on streets which are wide."*
N01	*"Probably a big road, cause there is more space which is more open."*
N02	*"I'd try to pick up a street that was a narrow street, that was not used very much like down the side of a building or something like that."*
N03	*"I would prefer the smaller one because of not so many people and also because of the protection from the buildings."*
N05	*"I would try to cut through the small roads, side streets."*
N06	*"Going down back streets ... you might get yourself quite lost and also there is a risk of it to become a dead end. While pedestrian areas and main roads usually have an open access."*
N09	*"I would zigzag and take the smaller side roads."*
N10	*"I think it would be a sort of middle sized road. I would not want to go to a narrow street, but equally I would not want to go to a busy main road."*
N11	*"I can't imagine that I would choose a narrow road. I would not feel safe in an enclosed environment probably because of buildings on a side."*
N13	*"I would take the widest road, the one I could see down the best."*
L02	*"I would prefer wider streets."*
L04	*"I would do the narrower side streets."*
L05	*"I would be more attracted by more open spaces, I guess, rather than narrow streets and alleyways."*
L08	*"I would stick to the main roads because they are big and wider."*
L09	*"Just small streets, it does not matter if they are pedestrianised or not."*
L10	*"I would probably choose the one which appears to be the most open, so probably the one which was sort of widest."*
L11	*"Find yourself quiet smaller street and just head as far away from it as you can."*
	People
P4	*"Follow people where they are going."*
N01	*"I would probably try to stay away from the crowds."*
N02	*"I would follow people because if I was in an unfamiliar place, these people might know where they were going and there is safety in numbers."*
N03	*"Not a road that is packed with people already."*
N05	*"I would avoid large crowded roads."*
N08	*"I think you might be better off all staying together."*
N09	*"I think I also would like security of people."*
N10	*"I would try to avoid pedestrianised area with lots of panicking people."*
N11	*"I would move with people. I suppose the feeling of safety in numbers ..."*
N13	*"I would go where it is the least crowded."*

L02	*"I would try to stay near people because that's where the help could come."*
L05	*"You might want to follow the crowd, but on the other hand they would obviously restrict your movement."*
L07	*"I would try to avoid streets from which people would be running towards me."*
L08	*"I would certainly pick quieter street with less people."*
L09	*"Quiet street that leads off the main areas where the most people would be."*
L10	*"I suppose, I would go for the one which seems the least busy."*
L11	*"I would not go with the flow of people."*
	Traffic
P3	*"Because if the cars stop, then it would be difficult because there could be pandemonium, you could be crushed."*
N01	*"Cars would restrict my movement."*
N02	*"Well, the cars would be terrifying."*
N05	*"I would avoid dual-carriage ways with heavy traffic."*
N06	*"I would prefer pedestrian area because you are less likely to have vehicle there."*
N09	*"I would rather go for pedestrianised areas to avoid panicking traffic."*
N10	*"To avoid lots of moving traffic like on dual-carriage way or so, because I would not be able to cross the road fairly easily."*
N13	*"I would thought the cars would probably be driving away very quickly. That's why I would try a road which was least busy."*
L02	*"Once you get on the roads you will get to meet with traffic which is stationary. I think you would like to be furthest away from the forming panic."*
L08	*"Cars would stop, so the road would be quite busy. I would stay away from the dual-carriage way, and stick to the quieter roads and pedestrian areas."*
L10	*"I think I would probably go for the one with least number of people or vehicles."*
	Familiar route
N01	*"I would go where I knew I was moving to."*
P4	*"I would navigate on streets which I know."*
N10	*"I would be walking down on streets I know."*
N11	*"I would take the route I know the best."*
N13	*"... only streets I know definitely where I was going."*
L02	*"That would be a route I know the longest."*
L04	*"I would take side streets because I am familiar with them."*
L05	*"I suppose, if I was familiar with any of them then I would probably take the familiar one."*
	Local amenities
P3	*"I would go into a shop to get cover of some kind."*
N05	*"Also I would avoid even single-carriage roads but with lot of shops, so lot's of people around."*
N08	*"I would avoid streets with shops, because people would be coming in and out."*
N10	*"I would try to avoid pedestrianised areas or any enclosed areas, like a shopping centre."*
N13	*"I would not go through any shops or buildings in case there were more bombs there as well."*
L03	*"I tend to avoid shopping areas, because again, it would be crowded."*
L07	*"I would prefer not to go down that way because that means again more people who would slow me down."*
	Secondary explosion
N01	*"In the past, bombers who have selected multiple targets have normally gone for busy areas."*
N02	*"You would think that maybe other bombs were going to go off."*
N03	*"There might be another bomb exploding."*
N05	*"I guess if there was a second bomb, that would be placed in very crowded area."*

N12	*"They have one bomb here and secondary explosion to catch people fleeing from the first one."*
N13	*"... if it was well away from the bomb, and there would not be anymore bombs ..."*
L10	*"There is a chance that there could be another bomb, there could be someone with a backpack."*
	Shortest and fastest route
N03	*"Not a road that is packed with people already, some place that I can see that I can move faster if I need to."*
N05	*"I would take the shortest way out of the city centre."*
N06	*"I would suspect as far away from the incident as quickly as possible."*
N07	*"I would probably just carry on in the straight line, shortest distance, I would not want to make any choices, just keep going."*
L03	*"I would take the shortest route."*
L07	*"I would try to go as direct as possible."*
L08	*"I would probably take the most direct route."*
	Emergency services
P3	*"I would wait there until a professional help arrive.*
N03	*"I would probably go to a place where I think I might get some information about what has happened."*
N11	*"If the road is narrow and you have got emergency services trying to come in, then there is not enough space for the people."*
N12	*"I would just stay where I am and wait for somebody to tell me what to do."*
N13	*"I would try to tell the police what I knew."*
L06	*"I would expect them to give me information."*
	Transportation accessibility
P4	*"I would be taking a bus, at least you know that the bus would be going from one place to another."*
N05	*"I would try to walk as far away as the city centre goes and get a taxi."*
N07	*"You would try to make your way back to where you can get a train from or a bus from or where you have your car to get away."*

Appendix I

Factors: Analysis of PEI Dataset

	Road width
P3	*"The road looks quite wide."* (22N)
P4	*"There is a lot of space, it is an open and big road."* (2L)
N01	*"It is having the space to move quickly, combination of the width of the road ..."* (10N)
N02	*"It is a wide street, I would put it higher up if I haven't know where it was."* (10N)
N03	*"This one is first because it is a relatively small street."* (16N)
N05	*"This one is the highest preference because it is a narrow side street."* (5L)
N06	*"It's a wide area."* (10N)
N07	*"I just did the order looking at the size of and width of the street and open spaces."*
N08	*"It is the space thing again, it looks wide and spacious."* (13L)
N09	*"I think it is too narrow, there can be a huge bottom neck."* (5N)
N10	*"It's a wide road."* (2L)
N11	*"It looks relatively wide."* (10N)
N12	*"It is a narrow street all the way up, it's like a funnel."* (5L)
N13	*"The road is not as wide, it does not seem as easy to get away."* (12L)
L02	*"I would try to avoid such side streets and walk on the main roads."* (25N)
L05	*"Nice and wide."* (1N)
L06	*"This one is fairly wide but a single-carriage way."* (6L)
L08	*"It's fairly wide, fairly open."* (6L)
L09	*"And it is not actually that narrow, it can fit two cars down the sides."*(5L)
L10	*"It's quite wide."* (1N)
L11	*"I would not head that way because it does look like it's narrowing down."* (4L)
	People
N01	*"There are not that many people around."* (10N)
N02	*"It does not look like a busy pathway that people would be thinking of taking."* (13L)
N03	*"It's quite empty, not too many people, that's the safest option."* (16N)
N05	*"It's not very busy at all so that would be my first choice."* (5L)
N06	*"There are not so many people."* (10N)
N09	*"There are not that many people."* (10N)
N11	*"There are not too many people."* (2L)
L02	*"The number of people that are panicking would influence your decision."* (9L)
L03	*"There are a lot of people there."* (2N)
L05	*"Not many people there."* (1N)
L07	*"There are no people around, so it's quick to walk down there."* (22N)
L08	*"It looks a little bit busy, but out of the options I think it's the best."* (25N)
L09	*"It looks like a quiet street, not too many people around."* (5L)
L10	*"You only have got people at the sides."* (1N)

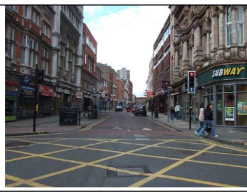
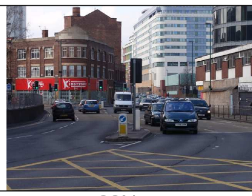
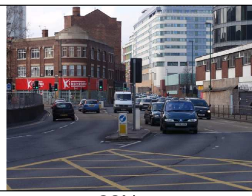
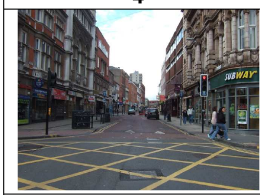
L11	*"Because there are not many people there."* (13L)
	Moving traffic
P3	*"There are no vehicles driving."* (5N)
N01	*"No cars, so I can walk straight down in the middle."* (10N)
N02	*"There are not that many cars there compared to some other pictures."* (13L)
N03	*"It's a main road, there are many cars around. So you have to be careful."* (26N)
N05	*"Not much traffic."* (5L)
N06	*"There is no moving traffic in this road."*(10N)
N09	*"It's not that busy. I can move, actually there are not that many cars."* (10N)
N11	*"It's a big junction. You can see road everywhere, and I think there would be a lot to think about as far as the traffic is concerned."* (33N)
N12	*"The traffic might be behaving unpredictably, then the road is actually not the safe place to be."* (3L)
N13	*"The cars don't seem to be stationary, they are all driving."* (2L)
L05	*"... not much traffic ..."* (1N)
L08	*"I think this is the best because if you are not going along this road you can end up having to watch out for cars."* (25N)
L09	*"It's more or less cars which you have to consider."* (12L)
L10	*"Although you immediately got cars around here, ..."* (4L)
L11	*"I know that this is a big busy road, so the moving traffic is gonna be dangerous."* (3L)
	Personal feeling
N03	*"I would probably go down this street or that street and find a narrower one ... because I would not feel safe to stay on this one."* (13N)
N05	*"I had a feeling that this is the main roads leading in and out of the city."* (25N)
N09	*"It is not too narrow but I would be worried. I would feel that something could fall on me if I was walking down in the middle."* (26N)
N10	*"It is starting to be a bit enclosed, I don't feel particularly safe."* (4L)
N11	*"You have got that feeling of walking towards an open space, which is reassuring."* (10N)
N12	*"It gives the impression of moving away from the city from the heavily built up area."* (2L)
N13	*It looks like it's a nice area, it looks really safe.* (2L)
L05	*"I just think that this one gives the least enclosed kind of felling."* (1N)
L08	*"It feels a bit more crammed because it makes the street darker, and feels more enclosed."* (28N)
L10	*"It looks quite to the edge of the city."* (4L)
L11	*"This one looks like it's heading to more suburban area, so it's obviously heading out of the city."* (2L)
	Physical obstacles
P3	*"Actually, get out of here is very difficult because of all the pedestrian railings."* (22N)
N02	*It's full of parked cars."* (10N)
N06	*"There aren't many parked cars."* (10N)
N10	*"I mean there is a van there half parked on the pavement."* (2L)
N11	*"Because of the bushes and stuff in front of me, I don't want to go and climb through the bushes, I want to run across a flat tiled or tarmac surface."* (26N)
N12	*"There is quite a lot of clutter on the street, you can see there are benches, and trees, and advertising boards, and bins and so on."* (25N)
N13	*"All these cars, parked cars ..."* (12L)
L02	*"There are lots of obstructions."* (25N)
L03	*"It's free of obstructions."* (1N)
L06	*"I have considered blockages in the street."* (n/a)
L08	*"Particularly because there are barriers here which would cram people."* (3L)
	Local knowledge

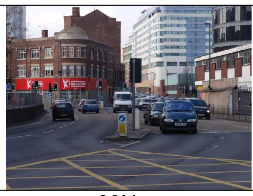
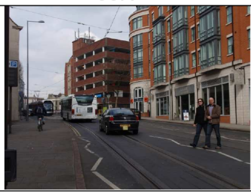
P3	*"I actually know this location and getting out of here is very difficult."* (22N)
N01	*"Although there is no traffic on this photo, this is probably a local knowledge, but you would not like to walk on this kind of street as a pedestrian because it's normally very busy."* (33N)
N02	*"I know is being the busiest street in Europe, and so, I don't like walking on it."* (2N)
N08	*"This is my first preference because I know where this is."* (22N)
N09	*"I am familiar with the area and where the road is taking me."* (26N)
N13	*"This one is just opposite the centre and there is no way I would go back into it."* (5L)
L02	*"The first picture I chose was the one which is the central ring road around, so it would be route that the emergency services would take in."* (3L)
L04	*"This would not be my preference because the train station is there."*(4L)
L06	*"I was thinking about getting home from the town centre."* (6L)
L07	*"I know that the last picture is really bad, I know that area."* (6L)
	Buildings
P4	*"Buildings all around, everything looks really close together".* (5N)
N01	*"I was looking at building types due to the possibility of secondary device."* (5N)
N03	*"I would probably feel safer if I am surrounded by higher buildings."* (16N)
N05	*"It looks like an area with offices and big buildings."* (25N)
N10	*"No buildings, quite a broad open space."* (2L)
N11	*"There is nothing high no tower blocks on either side."* (10N)
N13	*"And these buildings all seem quite well spaced apart."* (3L)
L05	*I think it's sort of ratio of building height to width of road. So even though, these buildings are quite high, because the space is nice and wide, that does not seem problematic."* (1N)
L08	*"There are not too many surrounding buildings."* (12L)
L10	*"You have got these big high buildings around."* (22N)
	Pavements
N03	*"I would probably stay on one side, because it is a wide pavement."* (10N)
N06	*"You have large straight pavements on either side."* (22N)
N10	*"The pavements are not really wide."* (4L)
N11	*"The pavements look fine, but if they stop there it's not safe."* (13N)
N12	*"Both sides have quite wide pavement."* (12L)
L08	*"Fairly big pavements."* (6L)
L11	*"You have got pavements to get onto to get away."* (2L)
	Road type
N03	*"It is a pedestrian street."* (5N)
N05	*"This is one of the main dual carriageway to go in and out of the city."* (3L)
N06	"*It's obviously a pedestrian area.*" (2N)
N10	*"It looks like a ring road."* (3L)
N12	*"It's fully pedestrianised area."* (25N)
N13	*"This one looks still quite safe, it is a dual-carriage way."* (3L)
L02	*"First picture I chose was the one which is the central ring road around."* (3L)
L08	*"It's pedestrianised route."* (25N)
	Exit routes availability
P4	*"There is a crossroad with many roads, so there are several options for people to consider."* (33N)
N02	*"There is an option to go that way, another option down there, so you have more options out."* (13L)
N08	*"You have several escape routes."* (22N)
N10	*"I can't see where this goes, there are no visible exists."* (25N)
N11	*A big junction, you can see road everywhere.* (33N)
N12	*"There are various kinds of side roads, and it feels like you have got options."* (12L)

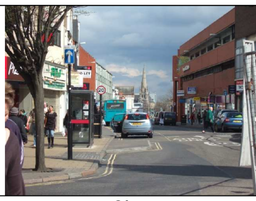
L05	*"Although the immediate escape route is good you are not quite sure what's gonna happen later on."* (5L)
L10	*"There are sort of few places, you have got different options to go."* (28N)
	Visibility
N09	*"This is an easy space to make the distance, it looks as it would lead somewhere, I am not putting myself into a cul-de-sac."* (10N)
N10	*"I can see all the way down there, it's maybe about half a mile away."* (12L)
N12	*"I need to be able to see a clear way."* (2L)
L03	*"I can see a long way into the distance."* (28N)
L08	*"You could see where you are going."* (6L)
L11	*"It does look like it's narrowing down, you don't see that far."* (4L)
	Road crossing difficulty
P3	*"You can't cross the road here."* (22N)
N03	*"It would be difficult to cross."* (10N)
N10	*"You could get across it fairly easily."* (2L)
N12	*"You can easily find that you are trapped, because you would have difficulties to cross it."* (5L)
L06	*"I do actually know that crossing here, and it's quite difficult, so it's not the easiest road to be a pedestrian on."* (3L)
L09	*"You would have to wait for lights to change if you wanna cross in safety"*. (3L)
	Local amenities
P3	*"There are plenty of shops to hide in and take cover."* (5N)
N05	*"There are not many shops around."* (5L)
N06	*"Quite lot of shops around, I assume if an incident happen near by, it would be very chaotic on the street."* (22N)
N08	*"I feel trapped, people would be coming out of the shops."* (2N)
L09	*"It's less retailer."* (12L)
L10	*"... all of the main shops are around ..."* (28N)
	Secondary explosion
N01	*"Possibility of secondary device because of the large car park."* (13N)
N05	*"It seems unlikely that a second bomb would be place there."* (2L)
N13	*"These buildings seem quite well spaced apart so if they have bombs in them, then you hope that it would miss you."* (3L)
L09	*"It looks also where the second attack would most likely to be."* (25N)
L10	*"I think it's not a place which is likely to be immediately targeted."* (22N)
	One way traffic
P3	*"The traffic only comes from one way."* (6L)
P4	*" its a one way only here."* (5N)
N06	*"But it's one way street, so under normal circumstances you expect cars only coming down in one direction."* (9L)
N12	*"Traffic is only moving in one way so, that provides some kind of predictability."* (12L)
L09	*"It is a one way street, so you would only think of cars going in one direction."* (6L)
	Transportation means
P4	*"The open space also means some facilities. You have means for transport."* (33N)
N03	*"There is a possibility of public transport there."*(10N)
N05	*"I would be able to get a taxi or take even public transport I think."* (12L)
L04	*"This would not be my preference because the train station is there."* (3L)
L10	*"You have got the bus stop."* (28N)

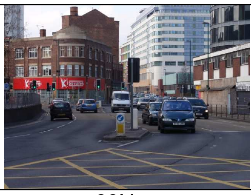
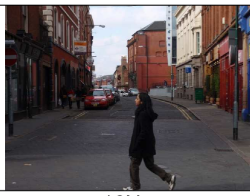
Appendix J

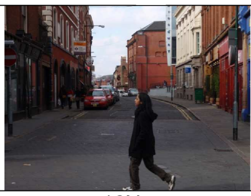
Organisation of Photographic Preferences

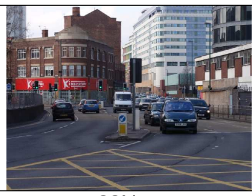
Pref.	1	2	3
P03	 5N	 6L	 33N
	4	5	6
	 2L	 5L	 22N
Pref.	1	2	3
P04	 2L	 33N	 22N
	4	5	6
	 6L	 5L	 5N

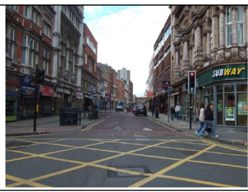
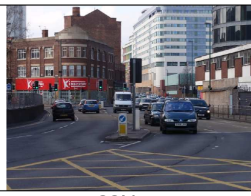
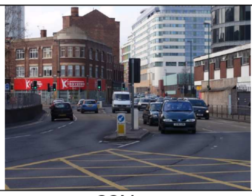
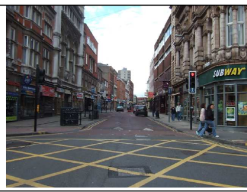
Pref.	N01	N02	N03
1	 10N	 13L	 16N
2	 26N	 22N	 10N
3	 16N	 9L	 13N
4	 33N	 17N	 33N
5	 13N	 10N	 5N
6	 5N	 2N	 26N

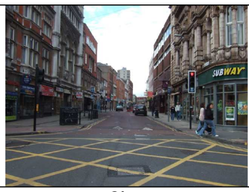
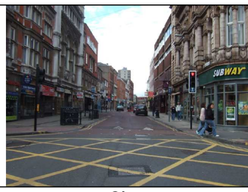
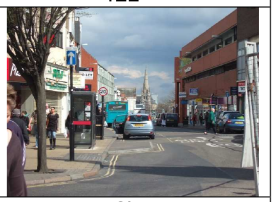
Pref.	N05	N06	N07
1	 5L	 10N	 3L
2	 2L	 2N	 25N
3	 12L	 9L	 12L
4	 4L	 17N	 2L
5	 3L	 13L	 4L
6	 25N	 22N	 5L

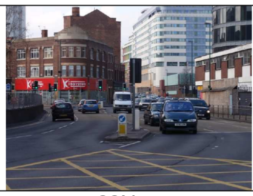
Pref.	N08	N09	N10
1			
	22N	10N	2L
2			
	9L	33N	12L
3			
	13L	26N	4L
4			
	17N	16N	25N
5			
	10N	13N	5L
6			
	2N	5N	3L

Pref.	N11	N12	N13
1	 10N	 2L	 2L
2	 33N	 12L	 3L
3	 16N	 4L	 12L
4	 26N	 25N	 4L
5	 13N	 3L	 5L
6	 5N	 5L	 25N

Pref.	L02	L03	L04
1	 3L	 28N	 2L
2	 12L	 1N	 3L
3	 9L	 5L	 13L
4	 6L	 17N	 4L
5	 5L	 22N	 5N
6	 25N	 2N	 9L

Pref.	L05	L06	L07
1	 1N	 6L	 22N
2	 28N	 5L	 5L
3	 2N	 3L	 2L
4	 5L	 12L	 33N
5	 17N	 9L	 5N
6	 22N	 25N	 6L

Pref.	L08	L09
1	 25N	 5L
2	 6L	 6L
3	 16N	 12L
4	 12L	 9L
5	 5L	 3L
6	 3L	 25N

Pref.	L10	L11
1	 17N	 2L
2	 1N	 13L
3	 28N	 16N
4	 5L	 3L
5	 22N	 5N
6	 2N	 4L

Appendix K

Preference in Navigation

Participant	SSI	Preferences of PEI
P3	n/a	wider roads
P4	*"I would navigate on streets which are wide."*	wider roads
N01	*"... probably somewhere in between. I would not want to be completely down the back streets."*	wider roads
N02	*", I'd try to pick up a street that was a narrow street, that was not used very much like down the side of a building or something like that."*	shortest route
N03	*"I would prefer the smaller one, because of the protection by the buildings "*	narrower roads
N05	*"I would try to cut through the small roads, side streets."*	narrower roads
N06	*"I would prefer the main streets they are more likely not end with a dead end or so."*	wider roads
N07	*"I would probably just carry on in the straight line, shortest distance, I would not want to make any choices, just keep going."*	wider roads
N08	n/a	wider roads
N09	*"I would zigzag and take the side roads towards somewhere I felt safe."*	shortest route
N10	*": I think it would be a sort of middle sized road, not a narrow one. I would not want to go to a narrow street, but equally I would not want to go to a busy main road, "*	wider roads
N11	*"An open space, a wide road, which gives you chance to run."*	wider roads
N12	n/a	wider roads
N13	*"The widest road, the one I could see down the best."*	wider roads
L02	*"I would keep to main streets unless I knew shortcuts which lead me through."*	wider roads
L03	*"I would follow the shortest route."*	wider roads
L04	*"I would go to the side streets."*	wider roads
L05	*"I would be more attracted by more open spaces, I guess, rather than narrow streets and alleyways."*	wider roads
L06	n/a	wider roads
L07	*"I would try to go as direct as possible but if I think that's where the incident happened than I would try to find some roads around it."*	n/a

L08	*"I, I would stick to the main roads, because I would get lost otherwise. And with the main roads, they are big and wider and you know the way you were going and it would be fairly obvious, because there are signs."*	narrower roads
L09	*"I would probably take the minor ones, because I suspect less people would go that way."*	narrower roads
L10	*"I would probably choose the one which appear to be most open, so probably the one which was sort of widest."*	wider roads
L11	*"But maybe not on the main route where everyone is taking so it's going to be very busy and you could get pushed over if everyone is running like that."*	wider roads

Appendix L

Preferred Destinations: Nottingham Use Case

Appendix M

Preferred Destinations: Leicester Use Case

Appendix N

Point Pattern Analysis with R

```
# load file with initial positions of agents
agentPositions <-
read.csv("/home/centos/veRa/forR/BEM.csv", header = TRUE, sep = ",")
agentPositions <-
read.csv("/home/centos/veRa/forR/SAM.csv", header = TRUE, sep = ",")

# load coordinates into separate vectors
x <- agentPositions$Xcoord
y <- agentPositions$Ycoord

#get mark => eucl=BEM geog=SAM
m=agentPositions$mark
mark <- factor(m, levels = c("eucl", "geog"))

#import ASCII raster file
asp <- import.asc("/home/centos/veRa/mask/mask20mleic.asc")

#convert asc object to im object to be able
# to create a binary window
imageRaster <- asc2im(asp)
imageMatrix <- as.matrix(imageRaster)
WinRaster <- as.owin(imageRaster)

# create bivariate point pattern from initialPositions file
agentPoints <- ppp(x, y, window=WinRaster, marks=mark,
unitname=c("metre","metres"))
summary(agentPoints)
plot(agentPoints)

# Monte-Carlo simulation for Gcross function
# construct simultaneous critical bands which have the property
# that, under H0, the probability that G ever wanders outside
# the critical bands is exactly 5%.
env <- envelope(agentPoints, Gcross, i="geog",
j="eucl", nsim=39, nrank=1)
summary(env)

#plot all
envGplot <- plot(env, col=c("blue", "brown", "green", "black"))
savePlot("envGPlot.png",type="png")
```