Integrating Spatio-Temporal Data into Agent-Based Simulation for Emergency Navigation Support

PhD Research Proposal

Zhiyong Wang, MSc

GISt Report No. 58

GIS TECHNOLOGY

TU Delft

OTB Research Institute for Housing, Urban and Mobility Studies

Delft University of Technology

Integrating Spatio-Temporal Data into Agent-Based Simulation for Emergency Navigation Support

PhD Research Proposal

Zhiyong Wang, MSc

GISt Report No. 58

Abstract

Emergency navigation for first responders in changing disasters is a very complex task and creates a new set of challenges for researchers. A lot of research work on this direction has been done. Nevertheless, traditional navigation systems consider only one responder with a pair of start and end points and the considered obstacles in previous studies are static. Moreover, none of the previous work has investigated the added value of integration of the disaster simulation with emergency navigation system. The goal of the research is to support the navigation task for multiple first responders in disasters by introducing the agent-based modeling and simulation integrated with spatio-temporal data. The general problem we are going to address is "how to navigate multiple first responders to multiple locations avoiding multiple obstacles".

For our purpose, this PhD project will be conducted as follows. First of all, we are going to investigate novel approaches to help navigate multiple first responders to avoid multiple obstacles, including both static obstacles and moving obstacles. By incorporating predictions of obstacles, one is able to anticipate changes in the road network and take them into consideration in the route determination process. After that, we will take advantage of the developments in current disaster simulation technology and integrate the disaster simulation model corrected with real time data into our navigation system. A prototype integrated navigation system linked with database will be developed. Besides, to help first responders evaluate navigation results, an agent-based modeling and simulation system updated with real time measurements will be proposed.

ISBN: 978-90-77029-30-5
ISSN: 1560-024

OTB Research Institute for the Built Environment
TU Delft
Jaffalaan 9, 2628 BX, Delft, The Netherlands
Tel.: +31 (0)15 278 4548; Fax +31 (0)15-278 2745
Websites: http://www.otb.tudelft.nl/
http://www.gdmc.nl/
Email: GISt@TUDelft.nl

Contents

Chapter 1

Motivations

At 7:49 a.m. local time on Wednesday, April 14th, 2010, a huge earthquake struck Yushu County in the Qinghai Province of China (Figure 1.1). According to the Xinhua News Agency, 2,698 people have been confirmed dead, 270 missing, and 12,135 injured of which 1,434 are severely injured. Some 3,700 personnel from the Qinghai division of the People's Armed Police was sent to the region to aid in rescue efforts. Specialty personnel also arrived from neighboring provinces Gansu, Shaanxi, and Ningxia, as well as the Tibet Autonomous Region. However, to the only road linking Xining to the quake zone 1,000 km (620 miles) was choked by military trucks and convoys organized by private aid groups. And the traffic was so bad that relief agencies said it took them more than 24 hours to reach the quake zone with their supplies, more than double the normal time it takes. Snow and rain continued to fall on the earthquake zone, adding to the difficult delivery of relief goods. One of the main problems associated with this case is that the current navigation system in the rescue vehicles doesn't take into account any real time information about the disasters. If the crisis managers can utilize the information provided by the disaster simulation driven by real time data and predict the status of the traffic network affected by the disasters, they can improve their route planning to accelerate delivery of emergency aid to affected area.

On 09 May, 2011, Platte City, Mo. US. Five firefighters were seriously injured when two fire trucks collided head-on in rural Missouri. The fire trucks were both headed to a structure fire and had left from the same station, but the first truck was heading back to the scene after missing the driveway for the house. As the first apparatus swung around, it struck the second, severely damaging both vehicles. A careful analysis of the above case would reveal a problem that the existing navigation systems in the rescue vehicle are independent from each other, couldn't share the information with other rescue vehicles and lack unified routing planning. If the first responders in these trucks were equipped with a navigation system that informs them of the current location and predicted position of other moving objects and provides with re-routing services considering other rescue vehicles, these tragedies could be avoided.

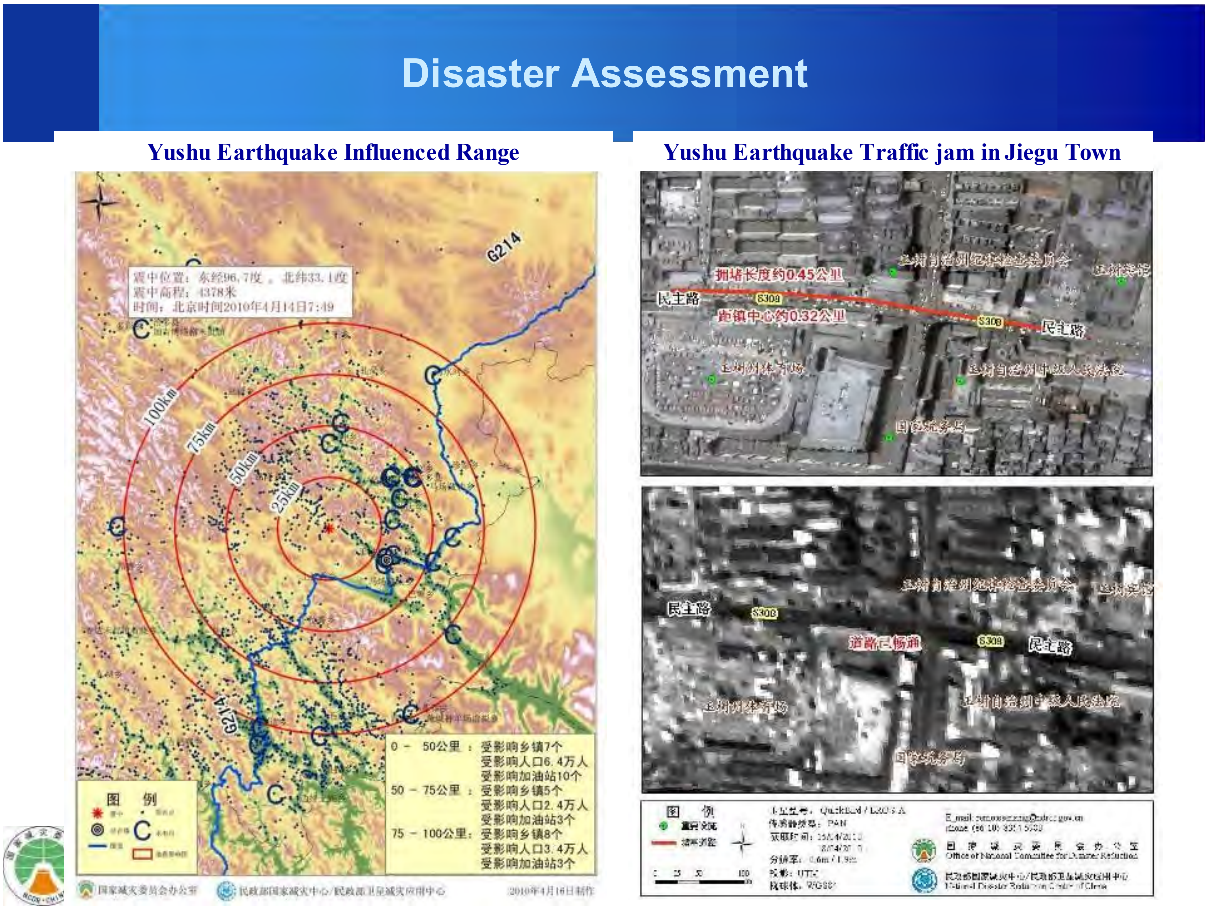

Figure 1.1: Yushu earthquake traffic jam (from Wang [2011])

In evacuation and rescue planning, it is advantageous for community leaders to have a thorough understanding of the human and geophysical characteristics of a community, be able to anticipate possible outcomes of different response and evacuation strategies under different situations, inform the general public and response units, and develop a set of evacuation and rescue plans accordingly. In order to achieve this goal, disaster managers in a community can use computer modeling techniques to simulate different disaster response strategies, use the results from these simulations to inform the public and first responders, and generate different evacuation and rescue plans under different circumstances. The complexity associated with evacuation and rescue planning in different disasters requires a computer modeling framework that can incorporate a number of factors into the modeling process. These factors include the nature of the disaster in question, the anticipated human behavioral patterns in the evacuation and rescue process, the unique geography and transportation infrastructure in a given area, the population distribution in the area, the population dynamics over different time periods, and the special needs of different population groups, etc. Agent-Based Modeling (ABM) within a GIS environment provides a promising approach that can be used to account for these factors in the modeling and simulation process (Bonabeau [2002]; Guo et al. [2008]; Shahriari and Tao [2002]; Wooldridge and Jennings [1995]).

Agent-based modeling is a type of microscopic modeling technique that addresses disaggregate characteristics of constituent units in a complex system and the dynamic interactions between these individual autonomous entities (Bonabeau [2002]). On one hand, ABM enables us to simulate the individual actions of diverse agents and measure the resulting system behaviors and outcomes over time. Agents act, interact with other agents, and react to their changing environment according to a set of behavioral rules derived from an underlying theory for the processes and interactions within a particular system (Macal and North [2010]). On the other hand, an agent-based approach can be used to emulate the behaviors of GIS analysts, assisting human users in managing vast amounts of geo-information including information extraction, information retrieval and filtering. All kinds of agents can be developed for providing help for human users to accomplish complex tasks or to carry out actions that may consume a large proportion of the user time (e.g. management of the dynamical data, searching and transformation of spatial data, retrieving and putting together appropriate data, etc.). Besides, machine learning techniques can be built in agents for prediction of disaster events and accidents (e.g. development of smoke, traffic jams).

Geographic information systems (GIS) allow to administrate and manipulate general information together with geographical data respecting its complexity and spatial relations (Schüle et al. [2004]). GISs perform four main functions:data entry, database management, spatial analysis and geographic visualization. GISs have at their core the conventional database management system (DBMS) which can provide special facilities for storage and structuring of geographic data. Another advantage that GISs can provide is the capability of transforming, manipulating and interpreting spatial data in order to study relationships between geographic features collectively. By adding a temporal (time) dimension to spatial data, GISs can perform sophisticated spatial-temporal analysis to keep track of objects, events and when and where these objects and events occur or exist ,and help identify trends that would otherwise be hidden in lengthy documents, which contribute to a general understanding of the entity dynamics. Through a process known as visualization, all kinds of graphics can be generated from 2D and 3D dataset (e.g. OSM data `http://www.openstreetmap.org/`, CityGML data `http://www.citygml.org/`) to help people understand results of geographical data analysis. Nowadays, GISs have been adopted widely in several application domains (Cova [1999]; Li et al. [2007]; Shahrabi and Pelot [2007]), ranging from ecological modeling to infrastructure maintenance. Decisions in emergency response, economy and administration, which are based on spatial information, are increasingly often made with the support of GIS software.

Our proposed GIS-enabled agent-based simulation system is a system that incorporates real-time measurements into the simulation process. It is an example of Dynamic Data Driven Applications Systems (DDDAS), where simulations are tightly coupled with real-time data stream. DDDAS is a paradigm whereby simulations and measurements become a symbiotic feedback control system (Darema et al. [2005]). DDDAS entails the ability to dynamically incorporate additional data into an executing application, and in reverse, the ability of an application to dynamically steer the measurement process (Darema [2004]). The DDDAS approach seeks to incorporate dynamic inputs into an executing application, which helps create simulation systems that can more accurately describe real world. This enables the simulation models that can be intelligently adjusted in accordance with evolving conditions and that infer new knowledge in ways that are not predetermined by the initialization parameters and initial static data. There exit a rich set of research projects investigating DDDAS approach and its application in multiple domains, such as weather and climate prediction, traffic management, systems engineering (Baldridge et al. [2006]).

In our research, we are going to improve GIS-enabled agent-based simulation using DDDAS approach to provide emergency responders with real-time navigation support. Our simulation model will include disaster models, responder models, management of moving objects and path finding algorithm that takes into account both stationary and moving obstacles.

Chapter 2

Related Work on Agent-Based Modeling, Geographic Information Systems and Dynamic Data Driven Application Systems

In the following sections 2.1, 2.2, we will begin with discussion of agent-based modeling, GIS and their applications in disaster management domain. Many researchers have been investigating the combination of agent-based modeling and GIS. The pros and cons of previous studies related to the integration of both technologies will be presented in section 2.3. After that, in section 2.6, we will introduce the Dynamic Data Driven Application System (DDDAS) approach that we are going to use to improve the agent-based simulation combined with GIS.

2.1 Agent-Based Modeling and Its Application in Emergency Management

Agent-based modeling and simulation has been applied to various domains (Ferreira and Borenstein [2010]; Iyetomi et al. [2009]; Konieczny et al. [2009]; Takahashi et al. [2002]; Zhan and Chen [2008]), especially in simulating disaster scenarios. Using an ABM, it is possible to evaluate policies and procedures for dealing with natural and man-made disasters. However, there are still some deficiencies of this approach. First, many present agent simulation models (Gonzalez [2009]; Ren et al. [2009]; Samuelson et al. [2010]; Zarboutis and Marmaras [2007]) lack GIS data to provide worlds that agents can respond to and function within, which reduces the realisticity of the simulations. Second, most current ABM simulations (Massaguer et al.

[2006]; Roßnagel and Junker [2010]) lack the simulation of disasters that have greatly impact on agent behaviors, which undermines credibility of their simulation results. The details of these works are provided below.

Zarboutis and Marmaras [2007] present a methodological framework for the design of formative evacuation plans for complex socio-technical systems in crisis. The framework adopts the complex adaptive systems modeling approach, and proposes the agent-based simulation as cognitive tool for developing formative evacuation plans. The person actions and the evacuees movement are modeled in the agent-based simulations as adaptive agents who exhibit reflexive, event-driven behaviors and respond to environmental stimuli at every point in time and space. The framework is demonstrated through an application to a metro system for the case of a tunnel fire. Figure 2.1 shows one of patterns at the level of passengers' behaviour. This involves a physical bottleneck which emerges when one or more physically capable passengers cannot move towards a specific location, due to the presence of obstacles, geometrical constraints etc.

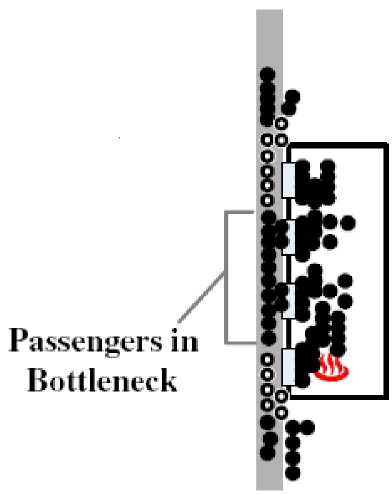

Figure 2.1: Passengers in bottleneck. The black dot represents passenger capable of escaping. The white circle corresponds to passenger that is incapacitated of escape (from Zarboutis and Marmaras [2007])

Gonzalez [2009] presents a crisis response simulation model architecture combining a discrete-event simulation (DES) environment for a crisis scenario with an agent-based model of the response organization. In multi-agent systems (MAS) as a computational organization, agents are modeled and implemented separately from the environmental model. In the proposed architecture, the environment is modeled as a discrete event simulation, and the crisis response agents are modeled as a multi-agent system. The simultaneous integration and separation of both models allows for independent modifications of the response organization and the scenario, which can be used to try out different configurations in the agent organization, to add new behaviors in the individual agents and to test the same configurations and behaviors in different crisis scenarios.

Roßnagel and Junker [2010] propose a system design for mobile emergency management and an approach for evaluating this system design using multi-agent based simulation. The proposed emergency management systems that utilize mobile communication infrastructures can provide prompt information delivery to save human lives. Each passenger is represented by an independent software agent. Each agent has a plan which comprises of a series of actions the agent performs or service the agent is using. Besides, agents are capable of walking around these obstacles and revising the plan in the case of an event occurs, for example a warning message on their cell phone. To make the designed simulation of passenger movements as realistic as possible, empirical data are collected from a large event as well as from normal rush hour traffic. However, this research doesn't include the simulation of disasters and gives no consideration to the impact of disasters on the agent's actions.

Ren et al. [2009] present an agent-based modeling and simulation to construct crowd evacuations for emergency response from an area under a fire. Various types of agents (i.e. man, woman and child) and different attributes (such as age, velocity, panic scale) of agents are designed in the presented simulation model. The attributes that govern the characteristics of the people are studied and tested by iterative simulations. Simulation results suggest several practical ways of minimizing the harmful consequences of such events and the existence of an optimal escape strategy. However, the presented simulation doesn't use the GIS data and is run on the simple environment "Grid", which fails to reflect the complexity of the real world.

Samuelson et al. [2010] develop agent-based computer simulation models of mass egress from a stadium and a subway station following one or more attacks with Improvised Explosive Devices (IEDs). People are represented as agents who try to progress toward known exits without entering excessively high-potential patches. Bomb explosions are represented as a wave of shock agents, propagated in all directions, and swarms of shrapnel agents flying level, at velocity diminishing over distance. Runs of the simulation models yield some interesting findings that improved real-time information systems which provide better guidance to exits would substantially expedite egress and could reduce secondary (trampling and crush) casualties. Also the simulation results indicate that models like these can be useful aids to selecting countermeasures, and for training, preparation and exercises.

Massaguer et al. [2006] present an augmented reality simulation environment called DrillSim for testing IT solutions in disaster response. The architecture of DrillSim is based on a multi-agent simulation. The simulation of the disaster response activity is achieved by modeling each person involved as an agent who has sensing and cognitive characteristics and can execute certain actions based on the observed world. The attributes of each agent (state, observed world, profile, social ties, agent behavior) dictate how the agent behaves. One of the key features of such a multi-agent based simulation where agents simulate humans is that it allows the editing of existing roles and the addition of new roles on demand, which enhances

DrillSim and makes it an extensible framework where new scenarios can be created and executed on the fly. The proposed methodology for managing agent roles is demonstrated with a series of experiments in the context of an evacuation.

In this research, the multi-agent system will be linked with GIS that provides geographical data for simulation models of both responders and disasters, enhancing the fidelity of our simulations.

2.2 GIS and Its Applications in Disaster Management Domain

GIS has been proven to be a useful tool for spatial analysis in emergency management, addressing the information needs of decision maker working with geographically referenced data. Once the event occurs, GIS–based incident command systems and consequence analysis tools can help emergency managers in the immediate response phase (Cutter [2003]). Nevertheless, there are still some impediments to application of GIS for real-time disaster decision support. GIS has limited capabilities for modeling and simulation, and most case studies that integrate GIS with modeling and simulation do not have a real-time capability (Zerger and Smith [2003]). In this research, various types of GIS data (2D and 3D) will be acquired from different data sources and integrated into agent-based simulation system to build valid and credible simulation model. Spatial databases serve as repository of all the data needed for the simulation. Spatial analysis functions will be performed to help first responders with evaluation of crisis situations and decision making. The following paragraphs give an overview of several aspects of applications of GIS in disaster management.

Kwan and Lee [2005] examine the potential of using real-time 3D GIS for the development and implementation of GIS–based intelligent emergency response systems (GIERS) that aim at facilitating quick emergency response to the attacks on multi-level structures (e.g. multi-story office buildings). The developed system is composed of several important components, including 3D GIS network data models, real-time and distributed geographic databases, mobile GIS technologies, and analytical and modeling methods. Important decision support functionalities of GIERS are also explored with particular reference to the application of network-based shortest path algorithms. The experiment results show that response delay within multi-level structures can be much longer than delays incurred on the ground transportation system, and GIERS have the potential for considerably reducing these delays, as shown in figure 2.2. However, a lack of the simulation of disasters that cause the described three types of uncertainty (road network uncertainty; entry point uncertainty; route uncertainty within a building) in emergency situations reduces the credibility of the demonstrated results.

Database Management Systems (DBMS) are an integrated and crucial component of most successful GIS. DBMS are used to store, manipulate and retrieve data from a database. A tight coupling with other technology can greatly enhance efficiency and productivity of DBMS in data management.

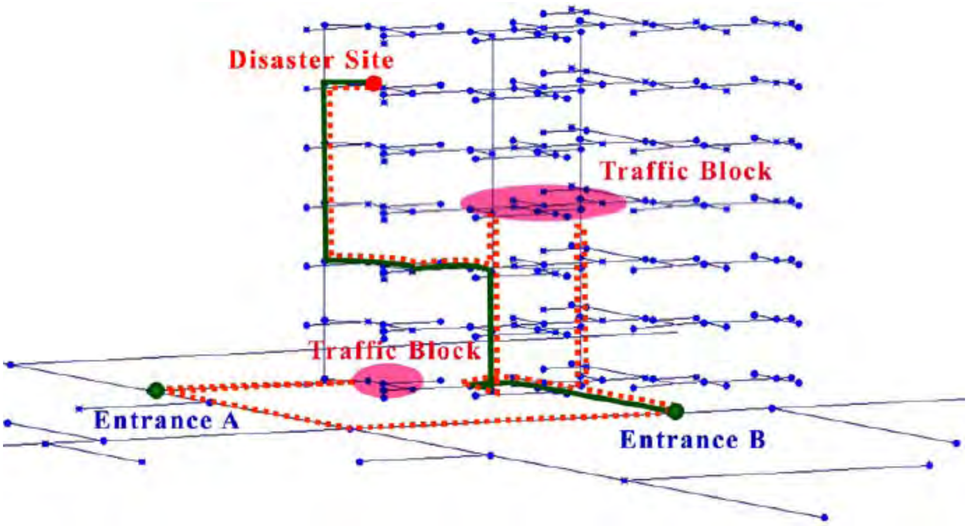

Figure 2.2: The shortest path between two entrances (A and B) and a disaster site on the 42th floor of the building. The green line represents shortest route using the system. The red dotted line corresponds to detour route without the system (from Kwan and Lee [2005])

Zlatanova et al. [2004] focus on the required developments at a database level (or middleware) to support response phase in disaster management. Three important aspects are addressed: a) Integrated management of multimedia information (graphics, text, video, raster), b) Ontology and semantic translators, c) 3D positioning to cope with emergency situations. It is believed that by providing targeted information and collecting relevant information from the field, the geo-information can facilitate the emergency handling in conjunction with knowledge approaches that is based on extraction of information from distributed database. Moreover, accurate 3D positioning is considered to be able to facilitate the logistics of emergency operations by providing 3D navigation capabilities in indoor and outdoor environments. In this research, different positioning systems will be considered and chosen for tracking the human movements, which provides the dynamic data to drive the simulations.

Zlatanova and Baharin [2008] report first results of research on the model and a set of analysis related to optimal navigation of mobile rescue units. Navigation cases of interest for first responders are organized in 7 groups with respect to type and multiplicity of source and destination points. Initial tests with simplified versions of the models were performed in PostGIS which is freeware and easy to employ. The possibility to maintain geometry and network (and shortest path algorithms on it) in one database also allow for further analysis and visualization. The models can be queried with respect to different spatial, spatio-temporal and non-spatial criteria. Other spatial data sets like topographic maps, orthophoto images, etc. can be used to enhance the analysis by providing surrounding information such as houses, gardens, etc. However, this research lacks the navigation simulation to evaluate the routing plan for each navigation case.

Geo-data gathered by numerous applications and by sensors placed in the environment plays a crucial role in the process of visual representation and analysis of hazardous events.

Zlatanova and Holweg [2004] promote geo-information and especially 3D geo-data in a support system for field workers and decision makers in emergency management. In the paper, the potential use of geo-information in any phase of emergency management, Mitigation, Preparedness, Response and Recovery, is pointed out. Besides, the paper discusses the research questions that have to be addressed (3D data structures, DBMS support of 3D topology, indexing, metadata, consistent update) and geo-data requirements for short time response and appropriate graphics user interface for work in stress situations. Another important aspect about utilisation and integration of geo-data, based on ontology and geo-semantics is also considered. However, they ignore the utilization of real-time geo-information in DBMS for simulation of disasters.

Kolbe et al. [2008] present CityGML and its potential utilization for different tasks in the context of emergency response. CityGML is in the first place ontology for the three-dimensional, multi-purpose, and multi-scale representation of cities, sites, and regions. The implementation of CityGML is based on the standard GML3 of the Open Geospatial Consortium and thus defines an exchange format for the storage of and interoperable access to 3D city models in SDIs. The class taxonomy distinguishes between buildings and other man-made artifacts, vegetation objects, water bodies, and transportation facilities like streets and railways. Spatial as well as semantic properties are structured in five consecutive levels of detail. CityGML could provide essential information for different aspects of disaster management, including assessing the damage caused by disasters, 3D visualization, localization in indoor and outdoor navigation and so forth. In this research, the CityGML data model will be used to provide the urban environment for agent-based simulation.

Göbelbecker et al. [2009] solve the common problem of getting the actual GIS data for almost any city in the world, by using the website OpenStreetMap.org, that provides mapping data for the whole world in a wiki-style concept, as the source of data. The data is converted to the format required by the Robocup Rescue Simulation System, enabling simulations on various real-world scenarios. The Rescue Simulation System integrated with real-world data in a GIS representation opens the opportunity for future contributions integrating position tracking of rescue forces, incident reports, and emergency calls and, looking further ahead, also the integration of agent frameworks as decision advisory. In proposed research, the OpenStreetMap data will also be considered and extracted to provide the environment with which agents interact.

In our research, we propose a novel approach that integrate GIS data into agent-based simulation to provide real-time emergency navigation support for first responders through connection with disaster simulation model.

2.3 GIS and ABM Integration for Disaster Management

Geographical Information Systems (GIS) are particularly useful tools for managing spatial information and provide powerful support in manipulating data about position, shape, extensions, etc. However, as mentioned before, traditional GIS tools are not well suited to dynamic modeling or simulations (Goodchild [2005]; Maguire [2005]). Agent-based modeling provides a way to express dynamics related to spatial elements, which can be achieved by the agents interactions and actions within a simulated environment. Therefore coupling ABM with GIS is highly attractive and there are several studies that have already combined both techniques (Batty and Jiang [1999]; Bo et al. [2007]; Brown et al. [2005]; Choi et al. [2009]; Khalesian and Delavar [2008]; Shi et al. [2009]; Tang and Zhang [2008]; Uno and Kashiyama [2008]; Yu and Peuquet [2009]). Nevertheless, these current approaches that combine the GIS and ABM are sill insufficient to support emergency navigation because these simulations are based on rigid input parameters and predefined models, and lack real-time data and the simulation of disasters, which greatly reduce the fidelity of the simulation. The pros and cons of these studies are presented below.

Batty and Jiang [1999] demonstrate that cellular automata (CA) and agent-based models provided a firm base for space time dynamics and illustrates these notions with three applications: finding shortest routes in systems where distance and direction are largely unknown but need to be explored by agents rather than computed geometrically; simulating the dynamics of water flow to model the evolution of river systems; detecting the geometric properties of space, which generates powerful results that are not possible using conventional geometry. But their simulation models, which don't include the essential features of emergencies, can't be utilized for emergency navigation purpose.

Epstein et al. [2011] introduces a novel hybrid of two fields–Computational Fluid Dynamics (CFD) and Agent-Based Modeling (ABM)–as a powerful new technique for urban evacuation planning. CFD is a predominant technique for modeling airborne transport of contaminants, while ABM is a powerful approach for modeling social dynamics in populations of adaptive individuals. The hybrid CFD-ABM method is capable of simulating how large, spatially-distributed populations might respond to a physically realistic contaminant plume. The overall feasibility of CFD-ABM evacuation design is demonstrated in the case of a hypothetical aerosol release in Los Angeles to explore potential effectiveness of various policy regimes. Figure 2.3 shows a screen capture from a simulation of this case. However, the proposed hybrid simulation model does't take into account the real time data, which undermines its feasibility in evacuation design in real disasters.

Khalesian and Delavar [2008] develop a functional prototype of spatio-temporal multi-agent system for the micro-simulation of highway traffic at the peak traffic times to find ways to increase highways' efficiency. A vehicle with a set of its own characteristics can be considered as an agent and a part of an environment i.e. traffic. It can also sense the environment by knowing other vehicles on road and how they move and interacts with others in a certain way. However, their developed framework doesn't consider the dynamics of disasters and

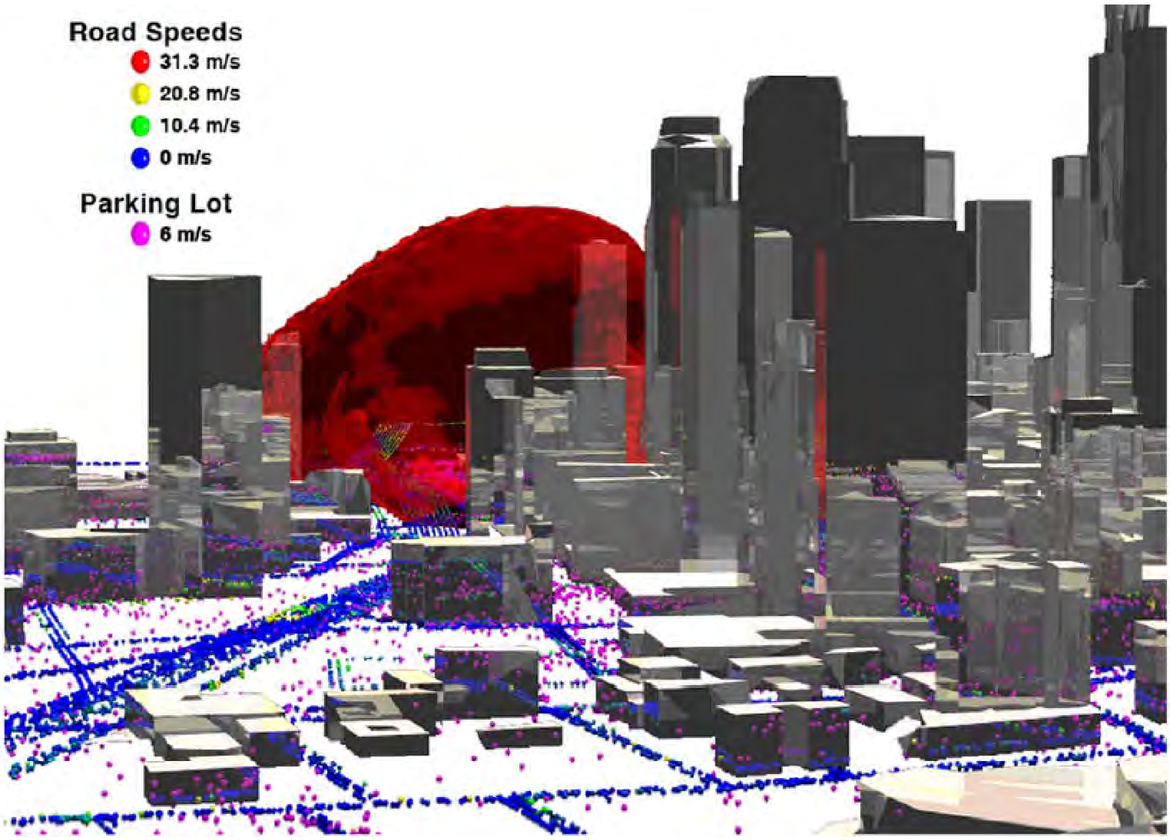

Figure 2.3: snapshot of simulation model with buildings as reflective polygons, the plume as a translucent red cloud and agents as spheres color-coded by speed (from Epstein et al. [2011])

their influence on responder's behaviors in the traffic network and can not provide guidance for emergency management.

Uno and Kashiyama [2008] present a simulation system for the disaster evacuation based on multi-agent system(MAS) considering geographical information. The proposed system comprises three parts: the modeling for the land and buildings using geographical information system (GIS) data, the analysis of disaster evacuation using multi-agent model, and the visualization for the numerical results using the virtual reality technique. In the MAS model, the refugees choose the evacuation routes based on the gravity model. The flood simulation is performed by the stabilized finite element simulation based on streamline-upwind/Petrov-Galerkin (SUPG) method. Figure 2.4, 2.5 show the simulation area and its bird view respectively. The system is applied to both the evacuation analysis by the flood flow in urban area and the investigation of the damage of human being by natural disasters. But, they don't study the influence of the information of moving objects (e.g. the spread of the flood, the movement of crowds) on refugees' route selection

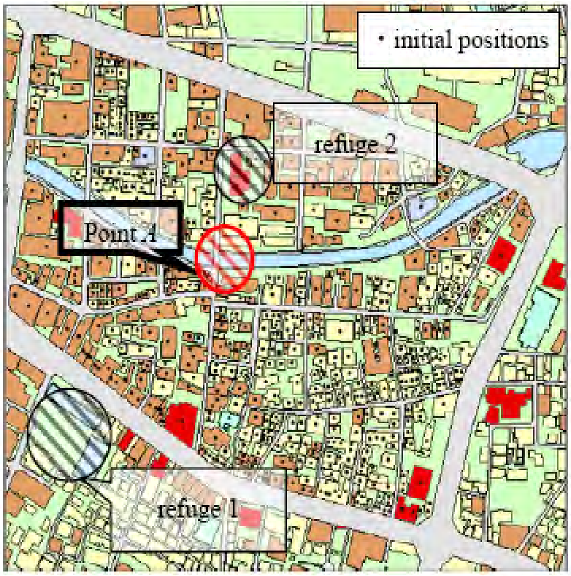

Figure 2.4: Simulation area (from Uno and Kashiyama [2008])

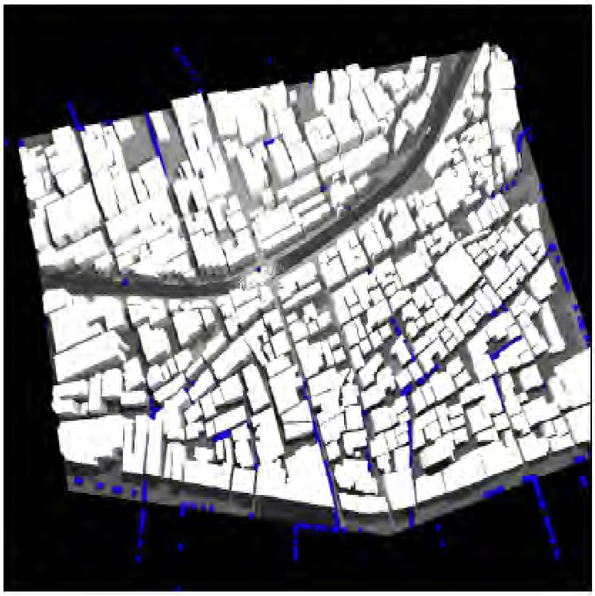

Figure 2.5: Bird view. The refugee is expressed by a blue sphere (from Uno and Kashiyama [2008])

Bo et al. [2007] present a multi-agent simulation framework based on Geographic Information System, investigating human behaviors during emergency evacuation. The Linear Weight Decreasing Particle Swarm Optimization (LWDPSO) was introduced to simulate individual's movement. The comparison of the results of the proposed model with social force model shows that multi-agent and modified PSO model well performs some typical evacuation behaviors. However, the evacuation results can only be displayed on two-dimensional map.

Brown et al. [2005] identify four key relationships that affect the interactions between geographic data(fields and objects) and agent-based (i.e., object-oriented) process models: identity, causal, temporal and topological. Furthermore, they described some alternative approaches to implementing GIS-ABM integration, focusing on an approach that involves development of middleware to manage connections between agents and spatial features, and some implementation issues. Four example models are presented to illustrate interactions between spatial data and spatial processes and the different requirements for integrating ABM and GIS functionality. Nevertheless, they don't address the issues that arise in the coupling of GIS-based data models with agent-based process models for emergency management (e.g. in the model of indoor evacuation, how to handle the relationship between agents and spatial features within a 3D environment).

Yu and Peuquet [2009] develop a kind of geographic agent (GeoAgents), integrated with expert systems, as a basic representation component to specifically address social and goal-driven behaviors that impact the earth and environmental systems, as well as to represent higher-level knowledge. A new conceptual representation framework, called FOTAR, is proposed to address the cross-scale processes of both social and natural interactions. The results of the application in a case study are presented for demonstration of its value in emergency management. However, the proposed framework is developed for environmental decision support and not applicable to emergency navigation or evacuation.

Shi et al. [2009] develop an agent-based evacuation model to simulate and analyze the egress progress in large public buildings through combining rule reasoning with numerical calculation. The proposed model consists of two sub-models, spatial environment model (SEM), which includes building layout information and fire field information, and agent decision model (ADM). The simulation results reflect the overall and dynamic process of occupants' evacuation under fire expansion, and the mutual relationship between occupants' safety and fire hazard. An indoor stadium used as a competition venue for 2008 Beijing Olympic Games has been taken into study as a case. However, the proposed model can only be applied to indoor environment.

Choi et al. [2009] integrate an agent-based model with 3D geometric network to calculate building egress time. A social force model is used to model the human behavior in a building. The evacuation route is based on the shortest path in a 3D geometric network in a GIS environment. The designed model can be applied further to evaluate more complex structures such as multi-story buildings and subway stations. However, the route determination process of the agent doesn't take the disasters into situation which reduces the credibility of simulation results.

Tang and Zhang [2008] present a 3D simulation model AutoEscape, which can simulate the evacuation process for any given occupant distribution in buildings. GIS technology provides the underlying support for environmental analysis to automatically generate the geometric representation and formulate the cognition of agents. The multi-agent based technology is employed to simulate the crowd behaviors with autonomously acting individuals. The results of a case study show the reliability and capacity of the proposed simulation model. But the modeling of human behaviors in evacuation doesn't include the impact of the moving objects (e.g. the crowds, the development of the disaster).

In our research, we are going to investigate the integration of spatio-temporal data with agent-based simulations to simulate the movements of first responders and to better support emergency navigation with predictions provided by disaster simulation models.

2.4 Dynamic Data Driven Application Systems

The decision making under dynamic uncertainty, especially in the crisis setting, creates new levels of requirements for the analysis and prediction capabilities of computer simulations.

However, traditional simulation models based on rigid input parameters, which are largely decoupled with real systems and make little usage of real-time data, fail to reflect the real disaster behaviors and reduce their ability of predictions. Therefore, we need a novel simulation system that is capable of adapting itself dynamically to the constant environment conditions changes, by means of real-time measurements. Such capabilities promise more accurate analysis and prediction, and more reliable outcomes that we can make use of for real-time emergency navigation support. Inspired by the Dynamic Data Driven Application Systems (DDDAS) concept, we explore new ideals to incorporate real time data into a running agent-based simulation model to provide better predictions of the movement of mobile objects (pedestrians, cars, etc.) and the changing disasters (plume, flood etc.) and to incorporate these predictions into the path planning process for first responders. DDDAS is an opportunity to formulate application simulation models and methods that incorporate/integrate dynamically measurement data, algorithms, system tools, and mathematical and statistical advances to produce effective simulation systems for important applications across the range of science and engineering disciplines (Darema [2004]). Our proposed work of agent-based simulation incorporated with real-time data is closely related to DDDAS. In our research, we will make use of existing disaster models corrected with real time measurements (e.g. fire model (Hu [2011]; Mandel et al. [2007]; Rodríguez et al. [2009])). The spread of these disaster models will be represented as the movement of obstacles that block the roads in the traffic network, to simulate the dynamics of disasters. As we obtain the predicted information of dynamics of the road network, these predictions will be incorporated into the path finding process to provide safe routes for first responders. Our proposed work can benefit from the following related researches on DDDAS.

Hu [2011] present a dynamic data driven simulation system that can be continually influenced by observation data of fire sensors, which is different from traditional simulations that make little use of the real time data. The proposed framework applies Sequential Monte Carlo (SMC) methods, also called particle filters, to the DEVS-FIRE simulation model to estimate the dynamically evolving fire front of a spreading fire. Figure 2.6 shows the dynamic data driven simulation framework based on SMC methods. The experimental results show that the proposed simulation model can provide a better prediction of wildfire spread.

Chaturvedi et al. [2006] create a Dynamic Data Driven Application System (DDDAS) to investigate the interaction between fire and agent models during a fire evacuation. Two independent models are used to simulate fire propagation and human evacuation. The created system allows real-time interactions, which can provide a better understanding of the factors (the exit position and width, evacuees' behaviors, etc.) that affect evacuation time and evacuation process. The results can be used for improving building design and regulations as well as training first responders.

Schoenharl et al. [2006] develop a Wireless Phone-Based Emergency Response (WIPER) system to provide emergency response managers with an integrated system that detects possible emergencies from cellular communication data, attempts to predict the development of emergency situations, and provides tools for evaluating possible courses of action in dealing

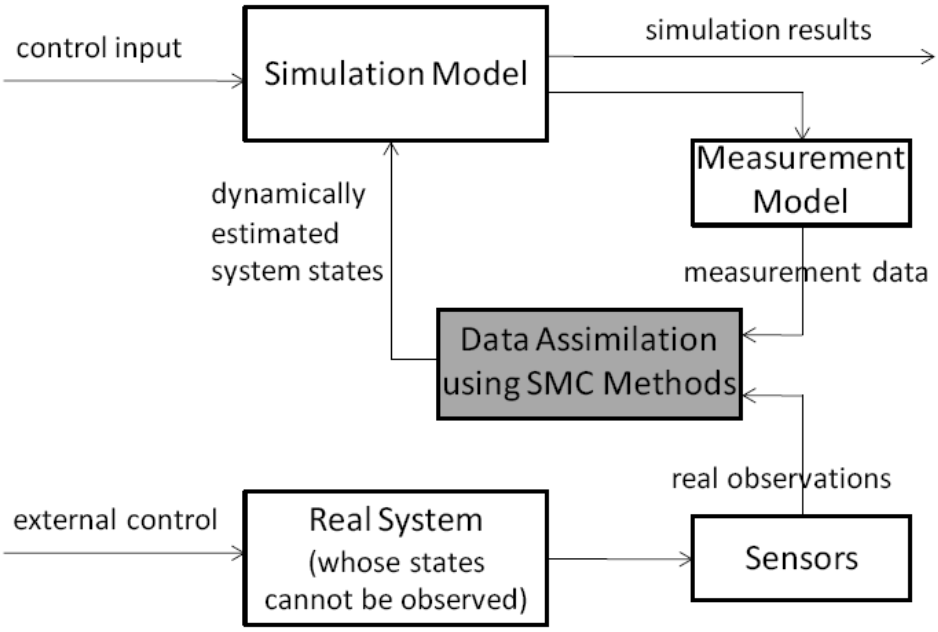

Figure 2.6: Dynamic Data Driven Simulation Framework Based on SMC methods (from Hu [2011])

with emergency situations. The system relies on the DDDAS concept, the incorporation of detailed real-time data to continuously update running simulations. The WIPER system utilizes a cell-phone network as a set of sensors to gather dynamic data from cell-phones and analyzes the incoming data using mobile agents to preprocess the data stream, providing the ability to detect potential anomalies (such as traffic jam).

Rodríguez et al. [2009] develop a DDDAS for forest fire spread prediction. The proposed system is capable of adapting itself dynamically to the constant environment conditions changes, by means of real-time measurements. They propose a two stage prediction method which couples two prediction schemes: a genetic algorithm that is used to generate a ranked set of parameter's combinations in term of prediction quality and a statistical approach that is to calculate the ignition probability of each cell. The real-time information regarding the fire's environment is injected into the execution environment and utilized for replacing the worst individual in the GA population. The experiment results obtained show that runtime data insertion improve prediction when conditions change suddenly during a fire.

Chaturvedi et al. [2005] build an integrated environment to study interaction among fire, structure and agent models in a fire evacuation from a typical office building. Fire Dynamics Simulator (FDS) is used to simulate the fire, providing time resolved temperature, CO, CO2, soot distribution in the building. The agent software is designed to simulate agent behaviors during evacuation by tracking the behavior of each individual in the building taking into

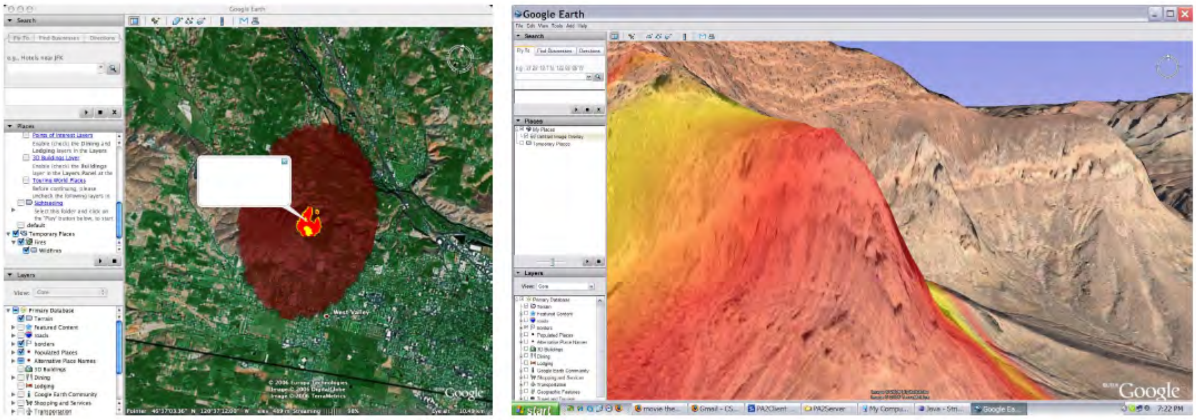

Figure 2.7: The Google Earth Fire Layering software tool (from Mandel et al. [2007])

account effects of temperature, CO, and soot on the behavior and health for each agent. The simulation results can be used for better fire safety building design and regulations.

Mandel et al. [2007] present an ongoing project which is to build DDDAS to use all available data for a short term wildfire prediction. The project involves new data assimilation methods to inject data into a running simulation, a physics based model coupled with weather prediction, on-site data acquisition using sensors and on-line visualization using Google Earth (see Figure 2.7). They develop a new method, called the morphing ensemble filter, to adjust both the intensity and the position of the fire.

In this research, to simulate actual disasters, we will start with the simple and move on to the complicated case (dynamic data driven simulation). We will simulate the dynamic of changing disasters using the moving polygons. Here two cases can be distinguished: 1) the polygon does not change of shape, i.e. the same polygon (kind of shape) is changing its position with time 2) the shape of the polygons changes and the position changes. These dynamics could make some parts of the network available again with the passage of time. After that, we will connect our model with disaster simulation corrected by real time measurements to more accurately predict impact of disasters on transportation network.

Chapter 3

Related Work on Management of Moving Objects and Routing Algorithms

This chapter will present two important components that are associated with navigation: management of moving objects and routing algorithms. There are a rich set of research works that contribute in these two areas and that we can consider and adapt for our emergency navigation purpose.

3.1 Management of Moving Objects

Many researchers have been working on managing moving objects. Tens of data models have been developed (Güting et al. [2006]; Meratnia [2005]; Speičvcys et al. [2003]) and various techniques are used to efficiently store, query and update trajectories of moving objects in spatio-temporal databases. However, the current data model for moving objects can not represent the high diversity and dynamic of the crises. For example, the data model for rescue units and evacuees should be different from each other. In addition to that, most works just use the information about moving objects for monitoring and tracking. We believe that the application of the moving object information in navigation for rescue units and the evacuees could facilitate the decision making process during the rescue operation and the evaluation of situations in disaster events.

The management of moving objects has been intensely investigated. Meratnia (2005) discussed the approaches for modeling and analysis of moving objects in Meratnia [2005]. Wolfson, et al. have proposed a Moving Objects Spatio-Temporal (MOST) model which is capable of tracking not only the current, but also the near future positions of moving objects in Sistla et al. [1997]; Wolfson et al. [1998]. Speičvcys et al. [2003] have presented a computational data model for network constrained moving objects. Šaltenis et al. [2000] propose a novel, R*-tree based indexing technique that supports the efficient querying of the current and projected future positions of such moving objects. Besides, the index problems of network constrained moving objects have also been studied in De Almeida and Güting [2005]. Cheng et al. [2004] study the execution of probabilistic range and nearest-neighbor queries over uncertain data for moving objects and developed algorithms for computing these queries for a generic object movement model.Güting et al. [2006] have proposed a fixed-network based MOD model with a rich set of data types and operations defined. However, the model is based on static transportation networks. To describe the spatio-temporal aspect of temporally variable transportation networks, Ding and Güting [2004] propose a State-Based Dynamic Transportation Network (SBDTN) model which can express the state and topology changes of the graph system.

The study of data models for moving objects is out of the scope of this research. However in this PhD research, some of these models will be selected and used for dynamic analysis and providing moving objects information to support optimal routing for emergency response.

3.2 Routing Algorithms

Quick and reliable routing and navigation are crucial for urban emergency response and disaster management. When the disaster occurs, the road network is full of complexity, such as multi-dimension, dynamics, uncertainty, etc., which makes the decision making in path finding quite difficult. For solving the problem of routing under emergencies, there is already a large number of deep research conducted within this area, ranging from classical search algorithms, Dijkstra algorithm, A* algorithm, etc. and their improvements, to development of intelligent algorithms which were originally inspired by natural evolution. All of these algorithms provide a rich set of solutions for route determination, however, they still have limitations. Classic algorithms (Bellman [1958]; Dijkstra [1959]; Hart et al. [1972]) can't deal with the network dynamics caused by the changing disasters and are applied to navigation for only one moving object. The algorithms proposed in Chen and Ji [2005]; Fu and Rilett [1998]; Hall [1986]; Miller-Hooks and Mahmassani [2000] can only be applied to the road network of which the probability density function of travel time is known beforehand, which is often not the case during disasters. The large computational complexity of intelligent algorithms (Dorigo and Gambardella [1997]; Holand [1992]; Kumar et al. [2009]; Rahman et al. [2008]; Yuan and Wang [2009]) doesn't satisfy the time-critical response requirement. In this research, to incorporate the dynamic data generated by the agent-based simulation into the path finding process, different routing algorithms will be considered and adapted into the outdoor navigation for first responders. Besides, the link with route determination in indoor environment will be considered to search the optimal path in urban areas (Lee and Zlatanova [2008]). More details about aforementioned algorithms are provided below.

Dijkstra's algorithm (Dijkstra [1959]), named after its inventor, has been influential in path computation research. It works by visiting nodes in the network starting with the object's start node and then iteratively examining the closest not-yet-examined node. It adds its successors to the set of nodes to be examined and thus divides the graph into two sets: S, the nodes whose shortest path to the start node is known and S', the nodes whose shortest path to the start node is unknown.

The A* algorithm (Hart et al. [1972]) is a heuristic variant of Dijkstra's algorithm. Similar to Dijkstra's algorithm, the search space is divided into two sets: S, the nodes whose shortest path to the start node is known and S', the nodes whose shortest path to the start node is unknown. It differs from Dijkstra's algorithm in that it not only considers the distance between the examined node and the start node, but it also considers the distance between the examined node and the goal node.

The Bellman-Ford algorithm (Bellman [1958]) can be used primarily for graphs with negative edge weights. The algorithm greedily selects the minimum-weight node not yet processed to relax. All adjacent vertices relaxed and updated in the distance array. The repetitions for all edges allow minimum distances to accurately propagate throughout the graph, since, in the absence of negative cycles, the shortest path can only visit each node at most once. Unlike the greedy approach, which depends on certain structural assumptions derived from positive weights, this straightforward approach can be extended to the general case.

Visser [2009] proposes a path-finding approach that takes into account changes in road network and predictions of future situations. A routing algorithm incorporated with predictions on plume movement and bridge openings and closings is developed based on the Dijkstra algorithm to decide whether it is better or wait or take an alternative route. Tests show that the estimation of travel time is more accurate and the calculated routes are faster and safer.

Fu and Rilett [1998] examine the dynamic and stochastic shortest path problem (DSSPP) of finding the expected shortest paths in a traffic network where the link travel times are modeled as a continuous-time stochastic process. A set of probability-based approximation models is developed to estimate the mean and variance of the travel time of a given path based on the mean and variance of the link travel times. Based on these relationships it is shown that the DSSPP is computationally intractable and traditional shortest path algorithms cannot guarantee an optimal solution. This paper proposes a heuristic algorithm based on k shortest path algorithm for solving the DSSPP where the dynamic and stochastic attributes of the link travel times are modeled by the mean and variance of the link travel time as a function of time of day. The trade-off between solution quality and computational efficiency of the proposed algorithm is demonstrated on a realistic network.

Miller-Hooks and Mahmassani [2000] address the problem of determining least expected time (LET) paths in stochastic, time-varying (STV) networks. Two specialized modified label-correcting algorithms are presented for the problem of generating LET paths in STV networks. The expected value (EV) algorithm, is presented for generating all a priori LET paths with their associated expected times from all origins to a single destination for each departure time in a given period. The expected lower bound (ELB) algorithm is proposed to determine lower bounds on the expected times of these a priori least expected time paths. Extensive numerical tests are conducted to illustrate the algorithms◎?computational performance as well as the properties of the solution.

Chen and Ji [2005] examine three definitions of optimality for finding the optimal path under an uncertain environment. These three stochastic path finding models are formulated as the expected value model, dependent-chance model, and chance-constrained model using different criteria to hedge against the travel time uncertainty. A simulation-based genetic algorithm is developed to solve these path finding models under uncertainties. Numerical results demonstrate that these stochastic path finding models and the developed algorithm could find a portfolio of paths to suit the travelers risk preferences towards travel time uncertainty in a stochastic network.

Hall [1986] introduces the problem of finding the least expected travel time path between two nodes in a network with travel times that are both random and time-dependent (e.g. a truck, rail, air or bus network). It first shows that standard shortest path algorithms (such as the Dijkstra algorithm) do not find the minimum expected travel time path on such a network, then proposes branch-and-bound for finding the least expected travel time path on this type of network. This approach differs from standard methods in that it utilizes travel time probability functions rather than expected travel times alone. Next, this paper shows that the optimal route choice is not a simple path but an adaptive decision rule. The best route from any given node to the final destination depends on the arrival time at that node. Because the arrival time is not known before departing the origin, a better route can be selected by deferring the final choice until later nodes are reached. Dynamic programming is proposed for finding the optimal time-adaptive decision rule.

Ant colony optimization is meta-heuristic approach inspired by the behavior of ants in nature that communicate with pheromones trails. While walking, ants deposit pheromone on the ground, and follow, in probability, pheromone previously deposited by other ants. Figure 3.1 shows the way ants exploit pheromone to find a shortest path between two points. This algorithm is proposed for solving hard combinatorial optimization problems and was first used to solve TSP problem (Dorigo and Gambardella [1997]), and has been successfully applied to other problems such as vehicle routing problem, quadratic assignment problem, scheduling problem and so on. Yuan and Wang [2009] propose an ant colony optimization algorithm to solve a multi-objective path selection model which is to minimize the total travel time along a path and to minimize the path complexity. A modified ant colony algorithm is designed in Rahman et al. [2008] for determination of the feasible route by calculating the shortest route and avoiding potential obstacles that appear in the building.

Genetic algorithm is a computational model simulating the process of genetic selection and natural elimination in biologic evolution. Pioneering work in this field was conducted by Holland in the 1960s (Holand [1992]). As a high efficient search strategy for global optimization, genetic algorithm demonstrates favorable performance on solving the combinatorial optimization problems. Kumar et al. [2009] propose a customized method based on a genetic

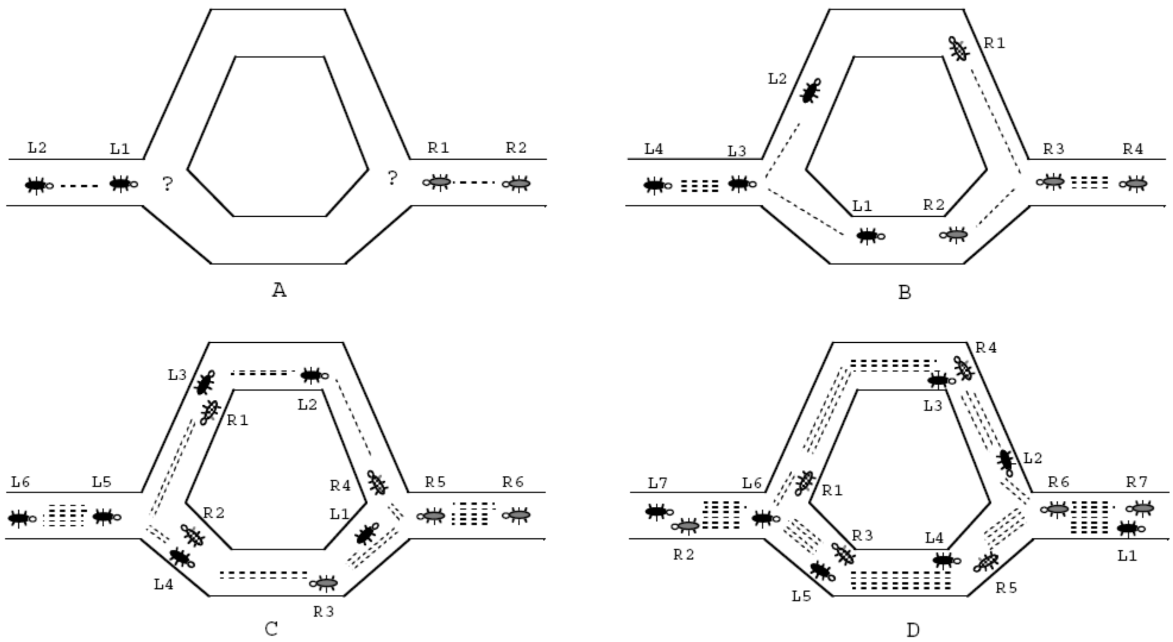

Figure 3.1: How real ants find a shortest path. The number of dashed lines is approximately proportional to the amount of pheromone deposited by ants. More pheromone accumulates on the shorter path (from Dorigo and Gambardella [1997])

algorithm to address the problem of GIS route finding on an actual map. But its application is limited to a static environment.

Nedkov and Zlatanova [2011] propose and implement a method for performing shortest path calculations taking constraints and obstacles into account. The method is built on top of Google Maps (GM) and uses its routing service to calculate the shortest distance between two locations. Users provide the constraints and obstacles in the form of polygons which identify impassable areas in the real world. The A* path-finding algorithm is used to guide Google's Directions Service around obstacles. Figure 3.2 shows the result of a routing request in Delft. However, the proposed method only considers the static obstacles and can't be applied into the dynamic environment during disasters.

Lee and Zlatanova [2008] propose a 3D Data Model for emergency response to represent urban built environments in multi-levels. The proposed data model is a composite model integrating: 1) 3D geometric model to measure and represent 3D spatial objects geometrically only; 2) 3D topological model to represent only the topological relationships among the 3D objects using a network-based model; 3) 3D city model to visualize the 3D objects in multi-views. To identify feasible and safe routes within a multilevel structure and to provide navigation guidance for rescue personnel, Dijkstra algorithm is modified and applied to the network

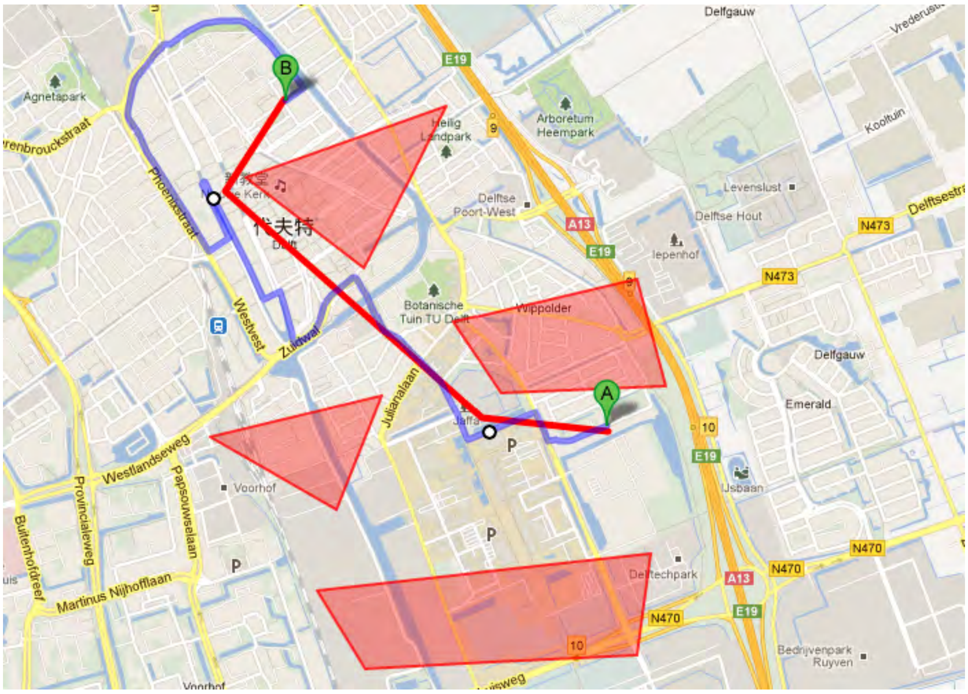

Figure 3.2: Calculated route result (from Nedkov and Zlatanova [2011])

problem 3D space. Experimental implementations of 3D topological analyses and 3D shortest route are presented in the paper.

In this research different routing and re-routing strategies incorporated with the updated real-time data of the network and predictions of disasters will be proposed for first responders and tested in the agent-based simulation.

Chapter 4

PhD Research

4.1 Research Objective

The goal of this research is to support the path planning for first responders with a navigation system and an approach for evaluating this system using multi-agent based simulation. The general problem we are going to address is "how to navigate 1:M responders to 1:N locations avoiding 0:L obstacles". We assume that the emergency navigation during disasters could be facilitated by the connection with the simulation of both disasters and first responders. To validate our assumption, in our proposed navigation system we will explore the way to utilize spatial data (static such as 2D/3D models and dynamic such as real time information of disasters) to provide routing services for first responders and re-routing in real time taking into account moving objects information in the road network and the evolution of disasters. An agent-based simulation system for emergency navigation for first responders will be designed and built to evaluate the navigation results. Each first responder is represented by an independent software agent that has a plan comprises of a series of actions and route plan. The agent model is updated with the real-time data. To facilitate the decision making process, various agents can be defined to support the information management and monitoring of the network. The effectiveness of the route plans will be assessed by observing the behaviors and interactions of the agents to help emergency managers develop strategies for better response.

4.2 Research Question

The main research question aimed at this research objective is:

What is the added value of agent-based simulation improved with spatial data (static such as 2D/3D models and dynamic such as real time measurements) to provide navigation support for first responders?

From the main research question, several sub-questions are derived to conduct a more accurate study of the research topic.

Questions related to the development of agents:

1. What types of agents should be developed to support emergency navigation and to simulate the responders' actions/movements and interactions with environmental factors?
2. What kind of user profile should be designed for route determination with the obtained information about the environment (e.g. the spread of the fire/plumes, obstacles distribution)?
3. What kind of rules should be designed for agents to dictate their actions?
4. How can we evaluate the behaviors of the agents (e.g. rescue vehicle agent)?

Questions related to GIS:

1. What kind of information will be needed for agent-based simulation? How to derive the network from these information?
2. What kind of relationships between agents and spatio-temporal objects will support the simulation?
3. What kind of data model should be used for management of the dynamic data that includes the real-time data, the information of moving objects (disasters, pedestrian, vehicles, etc.) and the output data of simulations? How these information will be structured in the database?

Questions related to the DDDAS approach:

1. What kinds of real-time information can be incorporated into the simulation model?
2. How to adjust the parameters of agent-based models with real-time data?
3. How to verify and validate the developed simulation model?

Questions related to the routing:

1. What kind of routing algorithms should be considered and adapted for path-finding, taking into account of the predictions of the disaster?
2. What kind of re-routing strategy should be designed for the agent to avoid moving obstacles?
3. How does the agent-based simulation system provide navigation services for both first responders and citizens?
4. On what kind of network (e.g. 2D and 3D) the algorithms will be run?

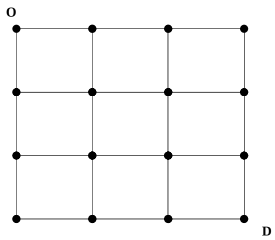

Figure 4.1: Simple network

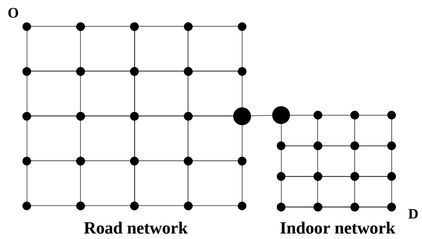

Figure 4.2: Nested network (One of the nests is a building)

4.3 Research Methodology

4.3.1 Literature Study and Technology Requirements

In order to understand the state-of-the-art progress in emergency management, an extensive literature review will be conducted. Previous work related to agent-based modeling, routing algorithms, GIS technology, etc. will also be investigated to provide support for this research. Moreover, technical information with respect to implementation issues should be taken into account. What's more, it is necessary to specify the characteristics and functions of the agents. An analysis of characteristics of the emergencies will be made for building the dynamic road network structure.

4.3.2 Conceptual Design

In this phase, we will design a multi-agent simulation framework integrated with spatio-temporal data. Within this system, several steps will be taken, including defining the types and functions of the agents, selecting a data model for moving objects, designing the model for storing the data and algorithms for emergency navigation and modeling the rescuer movements under disasters. Besides, the existing disaster models should be considered and included in the system to simulate the dynamics of crisis scenarios.

4.3.3 Implementation

This phase of the research aims at the development of agents and implementation of the designed system. Various agents and the selected data model of moving objects will be implemented in the system. In addition, the routing strategy will be designed and integrated into the multi-agent system.

Regarding the road network, we will start with simple environment, as shown in figure 4.1, then proceed with a more complex network, as shown in figure 4.2, and finally a real road network built from 2D/3D GIS data. Moreover, combining with these road models, we will implement the models of the disasters to simulate their effects on traffic conditions.

4.3.4 Validation and Adaptation

To validate the effectiveness of our designed navigation approach, an agent-based simulation framework will be proposed. Different navigation cases will be considered. The designed routing algorithms will be implemented in the agent model and tested in different scenarios. The navigation results will be assessed and demonstrated through agent performance and simulation results. Based on observation of agents' behaviors, improvements will be made to better support the path finding process in disasters. Besides, a comparison of the proposed navigation approach with others will be provided in respect to the performance of algorithms and agents.

4.4 The Architecture of The Prototype System

To validate the assumption that the coupling of the simulations with real-time data contributes to the prediction ability in crisis scenarios and to address the research challenges posed by DDDAS systems in Darema [2005], we are going to design concepts, rules (for agents), data models, etc., which are going to be validated by a prototype system. As shown in figure 4.3, the prototype system consists of several parts: data collection, data management, agent-based simulation model and data visualization. Agent-based simulation model is used to simulate natural disasters (e.g. plume, fire) that move across a certain road network, and to model the first responders and common people who can use heuristics algorithms to computes the routes. Database is used for data management and to store the geo-information of the network, the information of mobile agents (the routes, current position, starting point, end point, the status, etc.) and the real-time data collected from sensors and GPS receivers about the moving objects (disasters and people), and to provide location based service for first responders. 2D/3D GIS data (e.g. OpenStreetMap,GBKN, Top10NL) are supposed to model the spatial environment, especially the road network, and to store all the available 2D/3D spatial data including details of the objects within the environment. The simulation output data will be displayed to users through the laptop screen.

4.5 Investigations

We are going to validate our designed concepts, algorithms and data models with a GIS-enabled agent-based simulation system integrated with spatio-temporal data, which is also a dynamic data-driven application system (DDDAS) and is comprised of two components. One is proposed for simulation of rescuer movements, using the agent-based model corrected

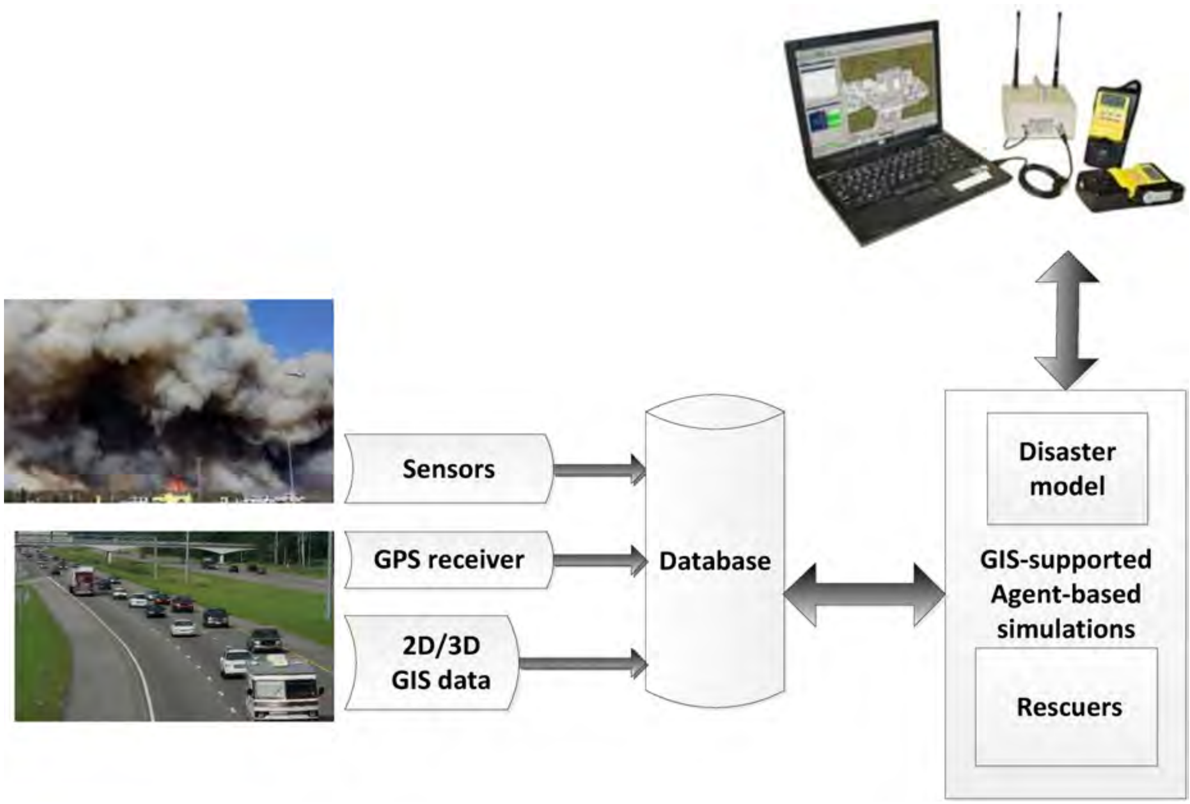

Figure 4.3: The architecture of the prototype system

with real-time data. The other is its extension with moving obstacles and is built for emergence navigation for first responders in disasters, using agent technology.

4.5.1 Investigation 1: Agent-based Modeling and Simulation of Rescuer Movements Updated with GPS Tracking, Considering Different Navigation Cases

In this phase, we will investigate the simulation of rescuer movements, using the agent-based model adjusted with the real-time data. We believe that agent-based simulation can benefit emergency navigation in at least two aspects: 1) the simulation itself has the ability to predict "future" situations with the "current" states as input, serving as a tool for achieving situation awareness. 2) the agent-based simulation could help evaluate the routing plan and modify it if necessary.

We are going to illustrate our ideas with a multi-agent framework that includes, but not limited to, following types of agents: agent that decides what kind of spatial information is

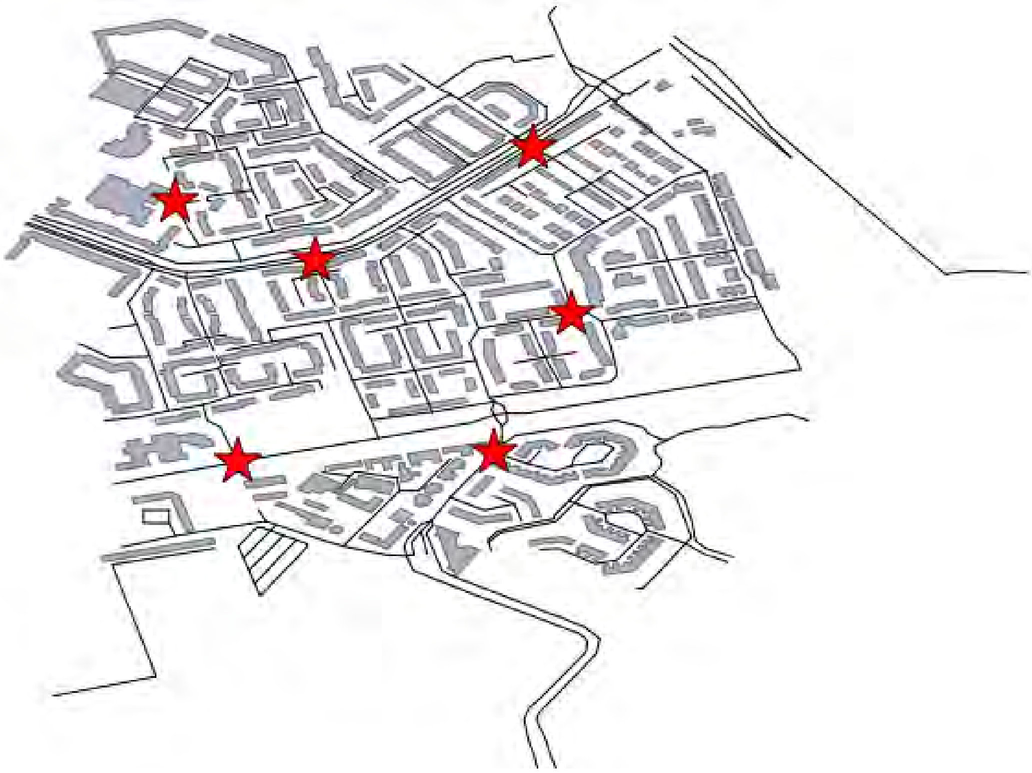

Figure 4.4: Snapshot of rescuer movements simulation

needed according to the user or the crisis scenarios; mobile agent that is used to model first responder; central control agent that updates the real time information of the network in the database and extracts real-time data from the database to correct the simulation; agent that provides the real time data. We model each first responder moving in the road network as an agent that possesses some parameters (i.e. position data, the planned route and state) and rules. As shown in figure 4.4. the red star corresponds to each responder agent. We also try to update the agent model with real time data and predict its next position and state in a short term. To be able to simulate the movements of rescuers, firstly, we classify the navigation cases into several categories. Then we are going to start from basic movements such as "one rescuer must go to help one citizen" to the most complex one, i.e. n rescuers must help m citizens and both the start and the target locations can be dynamic. We identify possible parameters of responders, such as start and end location, the number and positions of moving objects, optimal path etc. and use them to drive the simulation model. Later we will add more complexity by introducing more new parameters such as age, gender, modes of movement (walking, cycling, running, etc.) and so on.

The proposed system can be linked with an interface that aggregates the information from the agent-based simulation model and presents the real-time system status and predicted information to help crisis planners evaluate crisis situations and improve their plans. For example, the visualization interface can present rescuer's current and predicted positions. What's more, the designed interface can provide information about the number of the people who are closed to the disaster and the estimated number in the next half an hour or an hour based on simulation driven by the real-time data.

4.5.2 Investigation 2: Agent-based Modeling and Simulation for Emergence Navigation Among Moving Obstacles

Navigation during disasters is a very complex task because of the fact that a sound navigation system would have to take account of a number of concomitant factors. These factors include the moving speeds of both the first responders and the disaster, the distance between the target and the current position, the physical characteristics of the disaster (e.g. the shape). We assume that emergency navigation in disasters could benefit from a computer modeling framework that would simulate the development of the disaster. To validate this assumption, a new agent-based navigation system, which can be linked with disaster simulation to simulate the dynamics of the network affected by disasters (e.g. fire, plume), will be proposed to support path-finding for multiple responders among moving obstacles. This system will be comprised of several components, including multi-agent system for navigation, disaster simulation corrected with real-time data and visualization of simulation results.

In this investigation phase, the number of needed agents in the proposed multi-agent system will be much more. For example: 1) rescuer agent that is moving through the network; 2) agent called control center agent that monitors the network; 3), agent that provides the routing services; 4) agent that simulates the disaster; 5) agent that is user interface, provides the geo-information and sets the parameters of the simulations. In the initialization of simulation, the user interface agent collects the information (e.g. the start and end points, the speed of the agent, the initial position of the disaster) from users and loads the geo-information into the simulation model. As the simulation initialization process is finished, the mobile agent starts moving through the network. The disaster model updated with the real-time data is run in the background, and is visualized as a moving polygon (see Figure 4.5, 4.6). During the simulation process, the routing agent gathers the position data of the rescuer agent constantly, does spatial analysis in database (e.g. which road segments are closed), helps check the routes for the first responder to see if he is on the way to the dangerous area, re-calculates the route for the moving agent by applying heuristics based on the agent's local environment, and passes the calculated results to the responder agent. Control center agent is responsible for monitoring the dynamics of the network that is affected by the disasters, updates the data of the network in the database, and provides the updated data corresponding to the routing for other agents if necessary. Here we specify more about the rescuer agent that possesses attributes and characteristics that are important for the routing and evaluation of the route. The rescuer agent can have some attributes, such as the distance it has traveled so far, the

Figure 4.5: Snapshot of disaster simulation at time t

health index that is the function of the time when the agent is exposure to the pollutant or the poisonous plume, the complexity of the routing (i.e. the total junctions that the agent covers when it reaches its destination), the time from its starting point to the current position. Moreover, it can have some characteristics that determine its routing, i.e. different routing algorithms, such as Dijkstra, A* or other wayfinding algorithms and re-routing strategies that should be incorporated with the real-time and predicted information. Two types of real-time data will be used to aid the routing for first responders: 1) real-time data about the network (e.g. data from sensors that monitor the status of the network or first responders in the field who are patrolling around the area and collecting the information of the network (e.g. the closed nodes and edges); 2) real-time data from the sensors that capture movement characteristics of disasters that affects the road network (e.g. the direction and the speed of the wind). The first one can be used to identify the dangerous areas, and the latter will be incorporated into the disaster simulation model to predict the status of the road network in disasters. Since some parts in the network that are closed caused by the disaster could be available again, the agent should take decisions on whether it should wait for a certain amount of time or continue

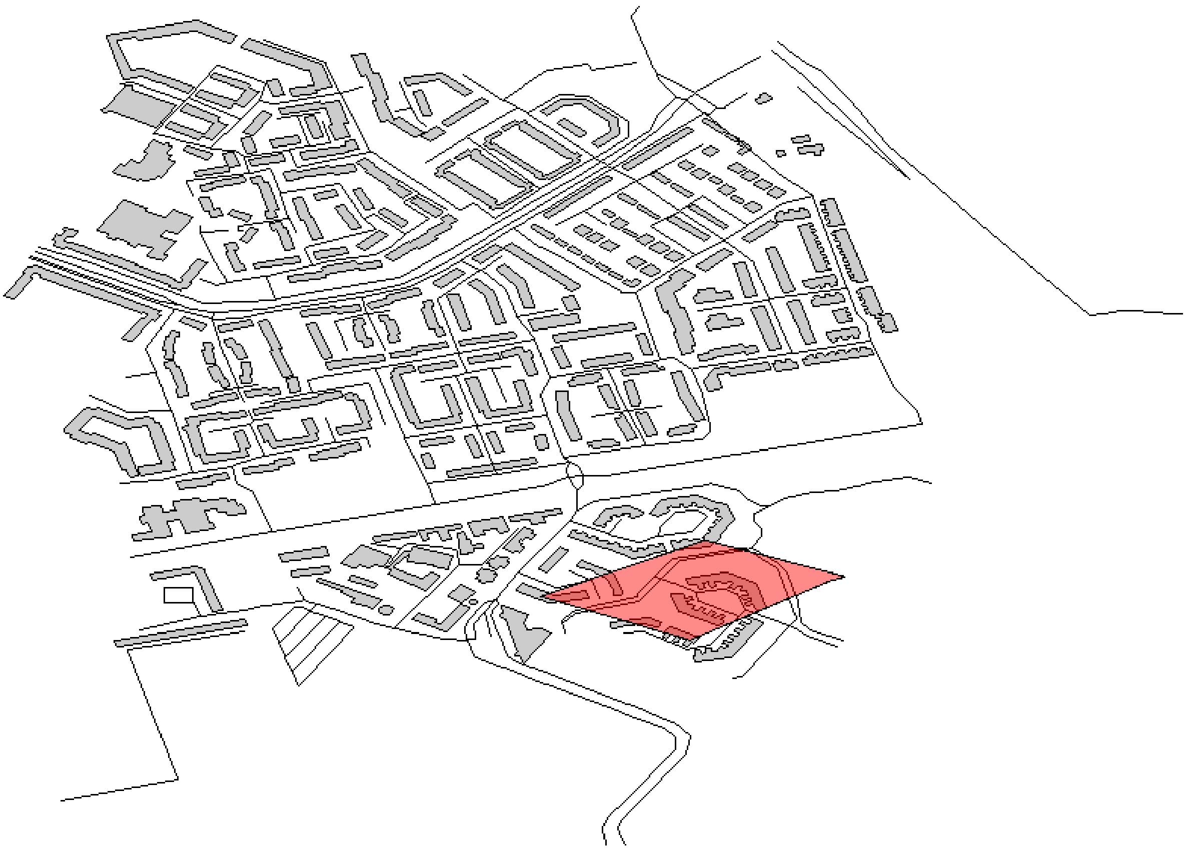

Figure 4.6: Snapshot of disaster simulation at time $t + \Delta t$

with its route to the destination. More types of agents and functions of agents will be added if needed.

4.5.3 Further development

One of further steps is to incorporate the proposed navigation approach into modeling and simulation of first responders to help valid and evaluate the navigation results. In addition to that, we can also do some extensions for aforementioned investigations: 1) In the agent-based approach for emergency navigation, considering that routing during crisis is also a multi-objective problem, a combination of optimization functions (e.g. safest, shortest, a minimum of time, least complexity), first responders might expect more options from which they can choose one of them based on their facing situations. In this case, intelligent algorithms with necessary adaptations are a promising approach to offer first responders a set of routes. Besides, the proposed approach is not limited to the outdoor navigation but can be used to aid indoor navigation for first responders. With appropriate adaption, the proposed approach can be also applied to the indoor environment so that first responders can be navigated both inside the building with routes along the structure of the building and in the outdoor environment. Furthermore, we can consider the case that many moving objects have to be navigated to a dynamic meeting point that is affected by disasters; 2) As to the modeling and simulation of movements of first responders, we can also explore influence of the communication on responder agents' moving behaviors.

Chapter 5

Practical Aspects

5.1 Related Software and Data

1. **Java**
   Java is a programming language and computing platform first released by Sun Microsystems in 1995. It is one of the most popular platforms for implementing large and long-lived applications. Java is free to download at `http://java.com`.

2. **Eclipse**
   Eclipse is the most widely-used IDE for developing Java applications. It is free, open-source, cross-platform, and provides plug-ins for a wide range of tasks. Available at `http://www.eclipse.org/`.

3. **Javascript**
   JavaScript is the most popular scripting language on the Internet, and works in all major browsers, such as Internet Explorer, Firefox, Chrome. It is one of the essential languages that you need to develop your web application.

4. **GeoTools**
   GeoTools is an open source Java library that provides tools for geospatial data. It is made up of a large number of modules that allow you to analyze, operate and visualize GIS data. Available at `http://geotools.org/`.

5. **Repast Simphony**
   Repast Simphony (Collier [2003]) is a free and open source agent-based modeling toolkit that simplifies model creation and use. One of Repast's attractive features is its ability to integrate GIS data (either raster or vector) directly into the simulation with relative ease. It is available at `http://repast.sourceforge.net/`. Our designed models will be mainly implemented in the repast.

6. **MASON**
   MASON (Luke et al. [2003]) is a fast discrete-event multi-agent simulation library core in Java, designed to be the foundation for large custom-purpose Java simulations. It has various GIS facilities including the import of vector data for spatial reasoning, distance calculations, determining coverage, and other functionality. Get the latest version at `http://cs.gmu.edu/~eclab/projects/mason/`.

7. **NetLogo**
   NetLogo (Wilensky [1999]) is a multi-agent modeling environment, providing a simple yet powerful programming language, built-in graphical interfaces and comprehensive documentation. Netlogo has a GIS extension which can be used to interact with spatial data. Get the latest version at `http://ccl.northwestern.edu/netlogo/`.

8. **PostGIS**
   PostGIS is an open source software program that adds support for geographic objects to the PostgreSQL object-relational database. It is available at `http://postgis.refractions.net/`.

9. **Oracle Spatial**
   Oracle Spatial is an extension to the Oracle DBMS that provides advanced spatial features to support high-end GIS and LBS solutions. Available at `http://www.oracle.com/technetwork/database/options/spatial/downloads/software/index.html`.

10. **ArcGIS**
    ArcGIS is a powereful suite consisting of a group of GIS software products produced by Esri. It provides a rich set of APIs (application programming interface) and tools to build a variety of GIS applications. More information can be found at `http://www.esri.com/`.

11. **GRASS**
    Geographic Resources Analysis Support System (GRASS) is a free software designed for data management, image processing, graphics production, spatial modelling, and visualization of many types of GIS data. Available at `http://grass.fbk.eu/`.

12. **Java 3D**
    An addition to Java for displaying three-dimensional graphics. It provides a set of universe utility classes for creating and manipulation 3D geometry and building the structures. It is available at `http://java3d.java.net/`.

13. **Bentley**
    A software that has powerful 3D tools for visualization and animation. More information can be found at `http://www.bentley.com`.

14. **Enterprise Architect**
    Enterprise Architect is a comprehensive UML analysis and design tool, covering all

aspects of the software development cycle. More information can be found at http://www.sparxsystems.com/products/ea/index.html.

For our simulations, generally there are two types of data that can be considered: 1) real data from the case; 2) synthetic data. Limited by the data availability, initially we will choose the second one to assess our prototype simulation system. The synthetic data will be set by hand or be generated from known models. Besides, 2D and 3D GIS data (e.g. OSM, CityGML, ect.) will be considered to be integrated into the simulation model to represent the actual landscape of the simulated real environment. For initial test, the available GIS data (such as Delft city (Figure 5.1)) is the first option taken into consideration.

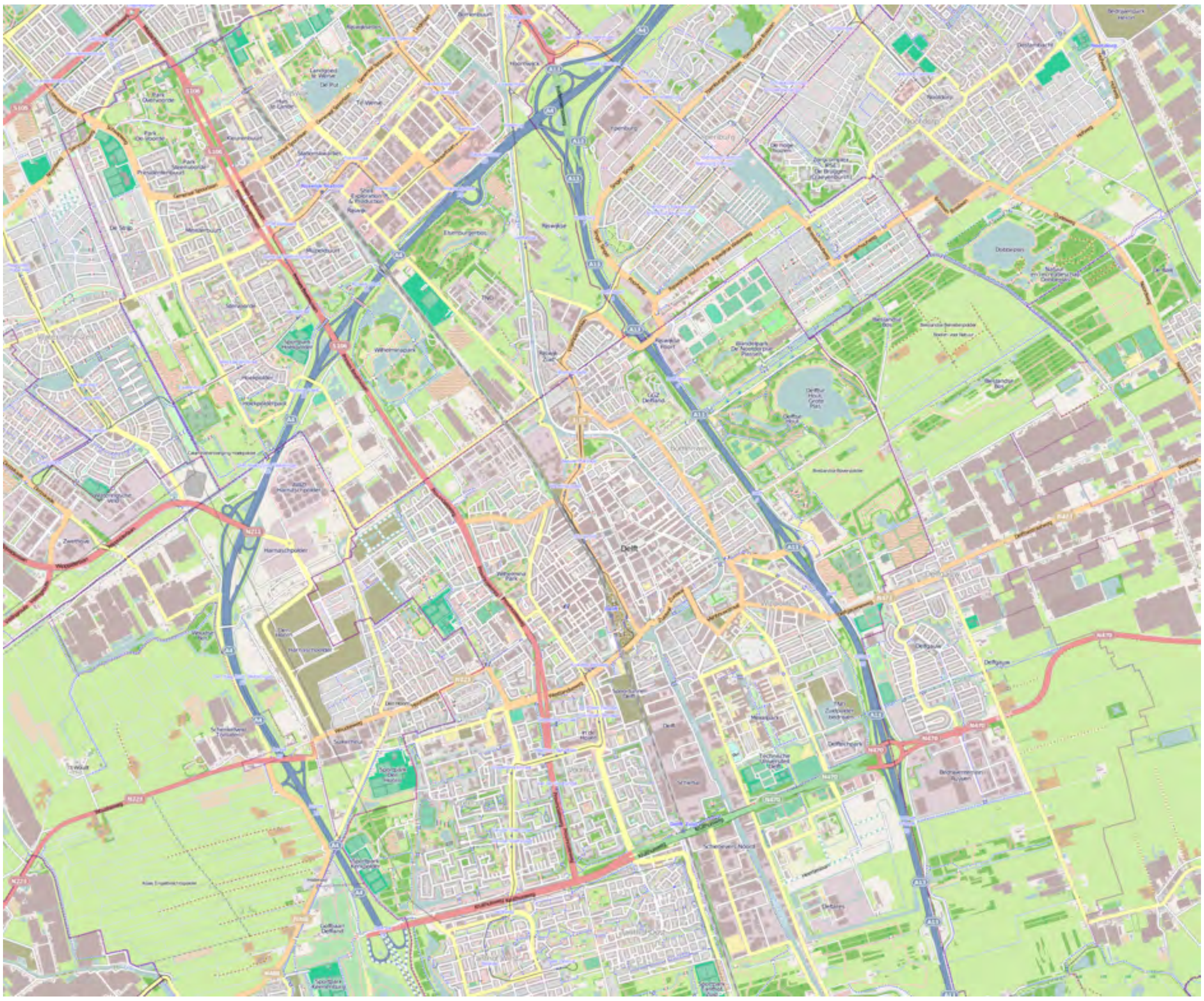

Figure 5.1: Delft city (from http://www.openstreetmap.org/)

5.2 Limitations

The following is a list of research topics that are in support of this research, but beyond its scope.

- Data model for moving objects
- Modelling of the disasters
- Real-time data collection

5.3 Supervisiion

This PhD project will be promoted by Prof. Dr. Ir. P.J.M. van Oosterom. Mw. Dr. Dipl. Ing. Sisi Zlatanova will be acting as daily supervisor. Supervision for this PhD project will be comprised of weekly meetings with Dr. Zlatanova and sporadic meetings with Dr. Ir. P.J.M. van Oosterom. Before every meeting, Zhiyong Wang will prepare a report. Current progress and research problems will be discussed during the meetings. Zhiyong Wang will also take notes, summarizing points of each meeting, and send them to supervisors before the next meeting.

5.4 Visits

In order to get to know the state of the art technologies and research results, some visits that are relevant to our research topics could be taken into account, which may include (but not limited to):

Institutes and universities: Ghent University which has some researchers working on location-based services; State University of New York at Stony Brook computational that has a lab focusing on computational geometry issues. It also could be nice to visit Vrije Universiteit Amsterdam that has groups doing research on geo-information technology for emergency management support. For disaster simulations, it is worthy communicating with researchers in TNO; Southampton University could be an option for knowing the current development of agent modeling and simulation for emergencies

Companies: Companies that are working on development of decision support systems for disaster management, e.g. Eagle systems.

5.5 Proposed timetable

The following is a time arrangement for the PhD research, which can be flexible according to the progress.

- Year 1:

  Aug. 2011 – Oct. 2011:
  This is the preparation phase for the PhD research, which focuses on literature review and technical preparation. Literature study. Investigate and understand the background of the PhD research. Technical preparation. Collect technical information and gain a good knowledge of different software tools, including Repsat, GeoTools, NetLogo, ArcGIS, PostGIS, etc. Extend the research plan. A first conference paper will be written based on this research proposal.

  Nov.–Jan. 2011:
  A investigation of the emergency navigation will be made for identify the navigation cases we are going to address. A specific case that many moving objects have to be navigated to one dynamic point will be considered. This simulation model will be implemented in an agent-base simulation system. An initial multi-agent simulation system corrected with GPS measurements will be designed considering different navigation cases.

  Feb.–Apr. 2012:
  A specific navigation case will be investigated and a possible solution will be proposed and implemented. A prototype system will be designed and tested to valid our proposed approach. A conference paper will be written based our results.

  May.– July. 2012:
  Improve the prototype system based on test results. A paper will be produced.

- Year 2:

  Aug. 2012 – Jan. 2013:
  A navigation algorithm taking into account moving obstacles will be designed. Besides, A simulation model that can simulate the movement of first responders will be implemented. This simulation system will be tested and improved based on simulation results. A conference paper will be produced.

  Feb. 2013 – Jul. 2013:
  Design a multi-agent system architecture that can monitor conditions of the road net-

work, track the locations of rescue vehicles, and provide first responders with navigation support. Another conference paper related to proposed system will be written.

- Year 3:

  Aug. 2013 – Jan. 2014:
  Integrate the multi-agent simulation model with the disaster model. Test the agent-based simulation system in different scenarios and analyze the agent behaviors and interactions in the developed system.

  Feb. 2014 – Jul.2014:
  Extend the work into 3D environment using GityGML.

- Year 4:

  Aug. 2014 – Jan.2015:
  Extend the work taking into account different disasters and communication between agents.

  Feb. 2015 – Jul. 2015:
  Assess and improve our systems. Write the thesis.

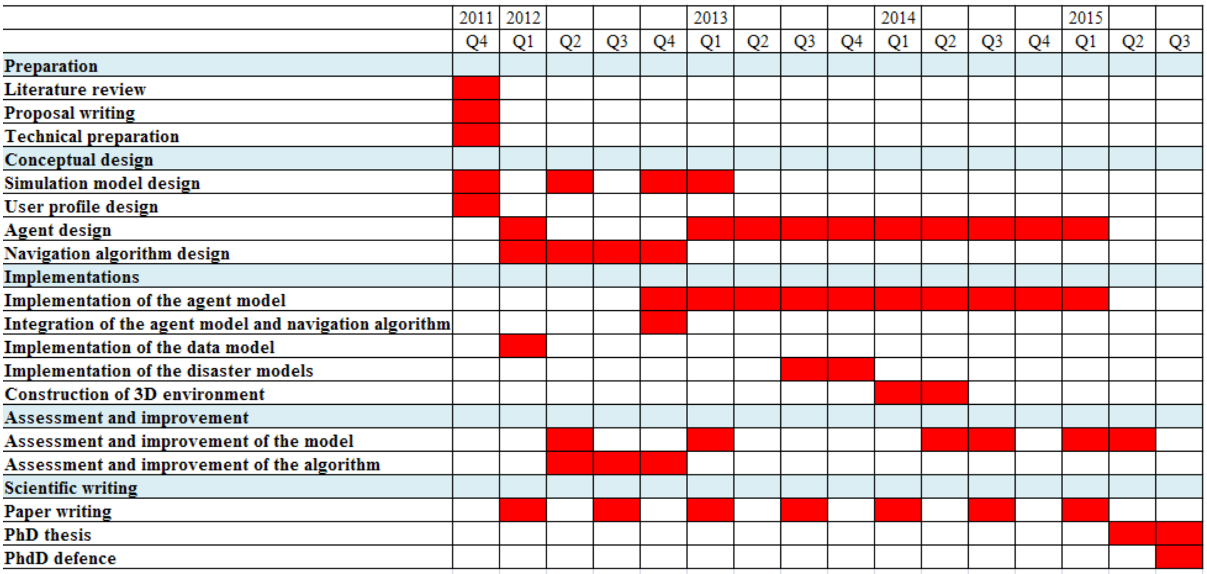

Figure 5.2: Research time schedule

5.6 Education

To gain a solid knowledge foundation for PhD research, the following courses will be taken. If more courses are needed, then this will be done through discussion with supervisors. Courses in MSc programme:

- 'Geo DBMS' (GE 1080)
- '3-D Geo-Information Systems' (GM 1020)
- 'Introduction to GIS' (GM 1041)
- 'GIS Principles Advanced Level' (GM 1050)
- 'Transportation and Spatial Modelling' (CT 4801)
- 'Traffic Flow Theory and Simulation' (CT 4821-09)

5.7 Articles

During this PhD career, a series of articles will be prepared for international journals and conferences.

- Regular reports
- 2 or 3 conference papers per year
  e.g. ISCRAM, AAMAS, DDDAS,UDMS, etc.
- 2 papers in reviewed scientific journals
  e.g. Computational Geosciences, Computers and Geosciences, International journal of emergency response
- PhD thesis

References

K. Baldridge, G. Biros, A. Chaturvedi, CC Douglas, M. Parashar, J. How, J. Saltz, E. Seidel, and A. Sussman. January 2006 DDDAS Workshop Report, National Science Foundation, 2006. URL `http://www.dddas.org/nsf-workshop-2006/wkshp_report.pdf`.

M. Batty and B. Jiang. Multi-agent simulation: new approaches to exploring space-time dynamics in GIS. *Graphical Information Systems Research - UK (GISRUK)1999*, 1999.

R. Bellman. On a routing problem. *Quarterly of Applied Mathematics*, 16:87–90, 1958.

Y. Bo, W. Cheng, H. Hua, et al. A multi-agent and PSO based simulation for human behavior in emergency evacuation. In *Proceedings of the 2007 International Conference on Computational Intelligence and Security*, pages 296–300. IEEE Computer Society, 2007.

E. Bonabeau. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(Suppl 3):7280–7287, 2002.

D.G. Brown, R. Riolo, D.T. Robinson, M. North, and W. Rand. Spatial process and data models: Toward integration of agent-based models and GIS. *Journal of Geographical Systems*, 7(1): 25–47, 2005.

A. Chaturvedi, A. Mellema, S. Filatyev, and J. Gore. Dddas for fire and agent evacuation modeling of the rhode island nightclub fire. *Computational Science–ICCS 2006*, pages 433–439, 2006.

AR Chaturvedi, SA Filatyev, JP Gore, A. Hanna, J. Means, and AK Mellema. Integrating fire, structure and agent models. *Computational Science–ICCS 2005*, pages 695–702, 2005.

A. Chen and Z. Ji. Path finding under uncertainty. *Journal of advanced transportation*, 39(1): 19–37, 2005.

R. Cheng, D.V. Kalashnikov, and S. Prabhakar. Querying imprecise data in moving object environments. *IEEE TRANSACTIONS ON KNOWLEDGE AND DATA ENGINEERING*, 16 (9):1112–1127, 2004.

J. Choi, S.G. Kim, J. Lee, and Y.S. Choi. Agent-based evacuation simulation for building structure evaluation. *GIScience & Remote Sensing*, 46(4):347–364, 2009.

N. Collier. Repast: An extensible framework for agent simulation. *The University of Chicago¡¯s Social Science Research*, 36(February 11), 2003.

T.J. Cova. GIS in emergency management. *Geographical information systems*, 2:845–858, 1999.

S.L. Cutter. GI science, disasters, and emergency management. *Transactions in GIS*, 7(4): 439–446, 2003.

F. Darema. Dynamic data driven applications systems: A new paradigm for application simulations and measurements. *Computational Science-ICCS 2004*, pages 662–669, 2004.

F. Darema. Grid computing and beyond: The context of dynamic data driven applications systems. *Proceedings of the IEEE*, 93(3):692–697, 2005.

Frederica Darema, Mario Rotea, Marvin Goldberg, and et al. DDDAS: Dynamic Data Driven Applications Systems,program solicitation 05-570,National Science Foundation, 2005. URL `http://www.nsf.gov/pubs/2005/nsf05570/nsf05570.htm`.

V.T. De Almeida and R.H. Güting. Indexing the trajectories of moving objects in networks. *GeoInformatica*, 9(1):33–60, 2005.

E.W. Dijkstra. A note on two problems in connexion with graphs. *Numerische mathematik*, 1(1): 269–271, 1959.

Z. Ding and R. Güting. Modeling temporally variable transportation networks. In *Database Systems for Advanced Applications*, pages 651–724. Springer, 2004.

M. Dorigo and L.M. Gambardella. Ant colony system: A cooperative learning approach to the traveling salesman problem. *IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION*, 1(1):53–66, 1997.

J.M. Epstein, R. Pankajakshan, and R.A. Hammond. Combining computational fluid dynamics and agent-based modeling: A new approach to evacuation planning. *PloS one*, 6(5): e20139, 2011.

L. Ferreira and D. Borenstein. Normative agent-based simulation for supply chain planning. *Journal of the Operational Research Society*, 62(3):501–514, 2010.

L. Fu and L.R. Rilett. Expected shortest paths in dynamic and stochastic traffic networks. *Transportation Research Part B: Methodological*, 32(7):499–516, 1998.

M. Göbelbecker, C. Dornhege, et al. Realistic cities in simulated environments-an open street map to robocup rescue converter. In *Fourth International Workshop on Synthetic Simulation and Robotics to Mitigate Earthquake Disaster (SRMED 2009)*, 2009.

R.A. Gonzalez. Crisis response simulation combining discrete-event and agent-based modeling. In *6th International ISCRAM Conference (ISCRAM2009), Gothenburg, Sweden*. Citeseer, 2009.

M.F. Goodchild. GIS, spatial analysis, and modelling overview. *Maguire, DJ, Batty, M. and Goodchild M, F.(eds.), GIS, Spatial Analysis and Modelling, ESRI Press, Redlands, California, USA*, 2005.

D. Guo, B. Ren, and C. Wang. Integrated agent-based modeling with GIS for large scale emergency simulation. *Advances in Computation and Intelligence*, pages 618–625, 2008.

R.H. Güting, V.T. De Almeida, and Z. Ding. Modeling and querying moving objects in networks. *The VLDB Journal*, 15(2):165–190, 2006.

R.W. Hall. The fastest path through a network with random time-dependent travel times. *Transportation science*, 20(3):182–188, 1986.

P.E. Hart, N.J. Nilsson, and B. Raphael. Correction to a formal basis for the heuristic determination of minimum cost paths. *ACM SIGART Bulletin*, (37):28–29, 1972.

JH Holand. Adaptation in nature and artificial systems, 1992.

X. Hu. Dynamic Data Driven Simulation. *SCS M&S Magazine*, pages 662–669, 2011.

H. Iyetomi, H. Aoyama, Y. Fujiwara, Y. Ikeda, and W. Souma. Agent-based model approach to complex phenomena in real economy. *Progress of Theoretical Physics Supplement*, 179:123–133, 2009.

M. Khalesian and MR Delavar. A multi-agent based traffic network micro-simulation using spatio-temporal GIS. *Center of Excellence in Geomatics Eng. and Disaster Management*, 10:31–36, 2008.

TH Kolbe, G. Gröger, L. Plümer, S. Zlatanova, and J. Li. Citygml–3D city models and their potential for emergency response. *Geospatial information technology for emergency response*, 6: 257, 2008.

M. Konieczny, J. Koźlak, and M. Żabińska. Multi-agent crisis management in transport domain. *Computational Science–ICCS 2009*, pages 855–864, 2009.

A.J.S. Kumar, J. Arunadevi, and V. Mohan. Intelligent transport route planning using genetic algorithms in path computation algorithms. *European Journal of Scientific Research*, 25 (3):463–468, 2009.

M.P. Kwan and J. Lee. Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments. *Computers, Environment and Urban Systems*, 29(2):93–113, 2005.

J. Lee and S. Zlatanova. A 3D data model and topological analyses for emergency response in urban areas. *Geospatial information technology for emergency response*, 6:143–167, 2008.

L. Li, L. Zhu, and D.Z. Sui. A GIS-based bayesian approach for analyzing spatial-temporal patterns of intra-city motor vehicle crashes. *Journal of Transport Geography*, 15(4):274–285, 2007.

S. Luke, G.C. Balan, L. Panait, C. Cioffi-Revilla, and S. Paus. Mason: A java multi-agent simulation library. In *Proceedings of Agent 2003 Conference on Challenges in Social Simulation*, volume 9, 2003.

C.M. Macal and M.J. North. Tutorial on agent-based modelling and simulation. *Journal of Simulation*, 4(3):151–162, 2010.

D.J. Maguire. Towards a GIS platform for spatial analysis and modelling. *Maguire, DJ, Batty, M. and Goodchild M, F.(eds.), GIS, Spatial Analysis and Modelling, ESRI Press, Redlands, California, USA*, 2005.

J. Mandel, J.D. Beezley, L.S. Bennethum, S. Chakraborty, J.L. Coen, C.C. Douglas, J. Hatcher, M. Kim, and A. Vodacek. A dynamic data driven wildland fire model. *Lecture Notes in Computer Science*, 4487:1042–1049, 2007.

D. Massaguer, V. Balasubramanian, S. Mehrotra, and N. Venkatasubramanian. Multi-agent simulation of disaster response. In *ATDM Workshop in AAMAS 2006*. Citeseer, 2006.

N. Meratnia. *Towards database support for moving object data*. PhD thesis, University of Twente, 2005.

E.D. Miller-Hooks and H.S. Mahmassani. Least expected time paths in stochastic, time-varying transportation networks. *Transportation Science*, 34(2):198–215, 2000.

Simeon Nedkov and Sisi Zlatanova. Enabling obstacle avoidance for Google maps' navigation service. In *Altan, Backhause, Boccardo & Zlatanova (Eds.), International Archives ISPRS XXXVIII, 7th, Gi4DM*, Anltalya, Turkey, 3-7 May 2011.

A. Rahman, A.K. Mahmood, and E. Schneider. Using agent-based simulation of human behavior to reduce evacuation time. In *Proceedings of the 11th Pacific Rim International Conference on Multi-Agents: Intelligent Agents and Multi-Agent Systems*, pages 357–369. Springer-Verlag, 2008.

C. Ren, C. Yang, and S. Jin. Agent-based modeling and simulation on emergency evacuation. *Complex Sciences*, pages 1451–1461, 2009.

R. Rodríguez, A. Cortés, and T. Margalef. Injecting dynamic real-time data into a DDDAS for forest fire behavior prediction. *Computational Science–ICCS 2009*, pages 489–499, 2009.

H. Roßnagel and O. Junker. Evaluation of a mobile emergency management system–a simulation approach. In *Proceedings of the 7th International ISCRAM Conference–Seattle*, volume 1, 2010.

S. Šaltenis, C.S. Jensen, S.T. Leutenegger, and M.A. Lopez. Indexing the positions of continuously moving objects. In *Proceedings of the 2000 ACM SIGMOD international conference on Management of data*, volume 29, pages 331–342. ACM, 2000.

D.A. Samuelson, M. Parker, A. Zimmerman, S. Guerin, J. Thorp, and O. Densmore. Agent-based animated simulation of mass egress following an improvised explosive device (IED) attack. *Pedestrian and Evacuation Dynamics 2008*, pages 605–609, 2010.

T. Schoenharl, G. Madey, G. Szabó, and A.L. Barabási. WIPER: A multi-agent system for emergency response. In *Proceedings of the 3rd International ISCRAM Conference*, 2006.

M. Schüle, R. Herrler, and F. Klügl. Coupling gis and multi-agent simulation–towards infrastructure for realistic simulation. *Multiagent System Technologies*, pages 228–242, 2004.

J. Shahrabi and R. Pelot. Hierarchical risk-based spatial analysis of maritime fishing traffic and incidents in canadian atlantic waters. *Geomatics Solutions for Disaster Management*, pages 335–350, 2007.

N. Shahriari and C.V. Tao. GIS applications using agent technology. *Annals of GIS*, 8(2):78–85, 2002.

J. Shi, A. Ren, and C. Chen. Agent-based evacuation model of large public buildings under fire conditions. *Automation in Construction*, 18(3):338–347, 2009.

A.P. Sistla, O. Wolfson, S. Chamberlain, and S. Dao. Modeling and querying moving objects. In *Proceedings of the Thirteenth International Conference on Data Engineering*, pages 422–432. IEEE Computer Society, 1997.

L. Speičvcys, C.S. Jensen, and A. Kligys. Computational data modeling for network-constrained moving objects. In *Proceedings of the 11th ACM international symposium on Advances in geographic information systems*, pages 118–125. ACM, 2003.

T. Takahashi, S. Tadokoro, M. Ohta, and N. Ito. Agent based approach in disaster rescue simulation-from test-bed of multiagent system to practical application. *RoboCup 2001: Robot Soccer World Cup V*, pages 63–74, 2002.

F. Tang and X. Zhang. A GIS-Based 3D simulation for occupant evacuation in a building. *Tsinghua Science & Technology*, 13:58–64, 2008.

K. Uno and K. Kashiyama. Development of simulation system for the disaster evacuation based on multi-agent model using GIS. *Tsinghua Science & Technology*, 13:348–353, 2008.

I. Visser. Route determination in disaster areas. Master's thesis, Utrecht University, Netherlands, 2009.

Lei Wang. Space Technology Application for Disaster Management in China, 2011. URL `http://www.unescap.org/idd/events/2011-Pakistan-Flood-Islamabad/06-Wang-Lei-Space-Technology.pdf`.

U. Wilensky. Netlogo: Center for connected learning and computer-based modeling. *Northwestern University, Evanston, IL*, pages 49–52, 1999.

O. Wolfson, B. Xu, S. Chamberlain, and L. Jiang. Moving objects databases: Issues and solutions. In *Proceedings of the 10th International Conference on Scientific and Statistical Database Management*, pages 111–122. IEEE Computer Society, 1998.

M. Wooldridge and N.R. Jennings. Intelligent agents: Theory and practice. *Knowledge engineering review*, 10(2):115–152, 1995.

C. Yu and D.J. Peuquet. A GeoAgent-based framework for knowledge-oriented representation: Embracing social rules in GIS. *International Journal of Geographical Information Science*, 23(7):923–960, 2009.

Y. Yuan and D. Wang. Path selection model and algorithm for emergency logistics management. *Computers and Industrial Engineering*, 56(3):1081–1094, 2009.

N. Zarboutis and N. Marmaras. Design of formative evacuation plans using agent-based simulation. *Safety Science*, 45(9):920–940, 2007.

A. Zerger and D.I. Smith. Impediments to using GIS for real-time disaster decision support. *Computers, Environment and Urban Systems*, 27(2):123–141, 2003.

F.B. Zhan and X. Chen. Agent-based modeling and evacuation planning. *Geospatial Technologies and Homeland Security*, pages 189–208, 2008.

S. Zlatanova and S.S.K. Baharin. Optimal navigation of first responders using DBMS. In *Joint Conference of the 3rd International Conference on Information Systems for Crisis Response and Management/4th International Symposium on Geo-Information for Disaster Management*, pages 541–554, 2008.

S. Zlatanova and D. Holweg. 3D Geo-information in emergency response: a framework. In *Proceedings of the Fourth International Symposium on Mobile Mapping Technology*, Kunming, China, March 29–31 2004.

S. Zlatanova, P. Van Oosterom, and E. Verbree. 3D technology for improving disaster management: Geo-DBMS and positioning. In *Proceedings of the XXth ISPRS congress*, Istanbul,Turkey, 12th–24 July 2004.

Reports published before in this series

1. GISt Report No. 1, Oosterom, P.J. van, Research issues in integrated querying of geometric and thematic cadastral information (1), Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 29 p.p.
2. GISt Report No. 2, Stoter, J.E., Considerations for a 3D Cadastre, Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 30.p.
3. GISt Report No. 3, Fendel, E.M. en A.B. Smits (eds.), Java GIS Seminar, Opening GDMC, Delft 15 November 2000, Delft University of Technology, GISt. No. 3, 25 p.p.
4. GISt Report No. 4, Oosterom, P.J.M. van, Research issues in integrated querying of geometric and thematic cadastral information (2), Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 29 p.p.
5. GISt Report No. 5, Oosterom, P.J.M. van, C.W. Quak, J.E. Stoter, T.P.M. Tijssen en M.E. de Vries, Objectgerichtheid TOP10vector: Achtergrond en commentaar op de gebruikersspecificaties en het conceptuele gegevensmodel, Rapport aan Topografische Dienst Nederland, E.M. Fendel (eds.), Delft University of Technology, Delft 2000, 18 p.p.
6. GISt Report No. 6, Quak, C.W., An implementation of a classification algorithm for houses, Rapport aan Concernstaf Kadaster, Delft 2001, 13.p.
7. GISt Report No. 7, Tijssen, T.P.M., C.W. Quak and P.J.M. van Oosterom, Spatial DBMS testing with data from the Cadastre and TNO NITG, Delft 2001, 119 p.
8. GISt Report No. 8, Vries, M.E. de en E. Verbree, Internet GIS met ArcIMS, Delft 2001, 38 p.
9. GISt Report No. 9, Vries, M.E. de, T.P.M. Tijssen, J.E. Stoter, C.W. Quak and P.J.M. van Oosterom, The GML prototype of the new TOP10vector object model, Report for the Topographic Service, Delft 2001, 132 p.
10. GISt Report No. 10, Stoter, J.E., Nauwkeurig bepalen van grondverzet op basis van CAD ontgravingsprofielen en GIS, een haalbaarheidsstudie, Rapport aan de Bouwdienst van Rijkswaterstaat, Delft 2001, 23 p.

11. GISt Report No. 11, Geo DBMS, De basis van GIS-toepassingen, KvAG/AGGN Themamiddag, 14 november 2001, J. Flim (eds.), Delft 2001, 37 p.

12. GISt Report No. 12, Vries, M.E. de, T.P.M. Tijssen, J.E. Stoter, C.W. Quak and P.J.M. van Oosterom, The second GML prototype of the new TOP10vector object model, Report for the Topographic Service, Delft 2002, Part 1, Main text, 63 p. and Part 2, Appendices B and C, 85 p.

13. GISt Report No. 13, Vries, M.E. de, T.P.M. Tijssen en P.J.M. van Oosterom, Comparing the storage of Shell data in Oracle spatial and in Oracle/ArcSDE compressed binary format, Delft 2002, .72 p. (Confidential)

14. GISt Report No. 14, Stoter, J.E., 3D Cadastre, Progress Report, Report to Concernstaf Kadaster, Delft 2002, 16 p.

15. GISt Report No. 15, Zlatanova, S., Research Project on the Usability of Oracle Spatial within the RWS Organisation, Detailed Project Plan (MD-NR. 3215), Report to Meetkundige Dienst – Rijkswaterstaat, Delft 2002, 13 p.

16. GISt Report No. 16, Verbree, E., Driedimensionale Topografische Terreinmodellering op basis van Tetraëder Netwerken: Top10-3D, Report aan Topografische Dienst Nederland, Delft 2002, 15 p.

17. GISt Report No. 17, Zlatanova, S. Augmented Reality Technology, Report to SURFnet bv, Delft 2002, 72 p.

18. GISt Report No. 18, Vries, M.E. de, Ontsluiting van Geo-informatie via netwerken, Plan van aanpak, Delft 2002, 17p.

19. GISt Report No. 19, Tijssen, T.P.M., Testing Informix DBMS with spatial data from the cadastre, Delft 2002, 62 p.

20. GISt Report No. 20, Oosterom, P.J.M. van, Vision for the next decade of GIS technology, A research agenda for the TU Delft the Netherlands, Delft 2003, 55 p.

21. GISt Report No. 21, Zlatanova, S., T.P.M. Tijssen, P.J.M. van Oosterom and C.W. Quak, Research on usability of Oracle Spatial within the RWS organisation, (AGI-GAG-2003-21), Report to Meetkundige Dienst – Rijkswaterstaat, Delft 2003, 74 p.

22. GISt Report No. 22, Verbree, E., Kartografische hoogtevoorstelling TOP10vector, Report aan Topografische Dienst Nederland, Delft 2003, 28 p.

23. GISt Report No. 23, Tijssen, T.P.M., M.E. de Vries and P.J.M. van Oosterom, Comparing the storage of Shell data in Oracle SDO_Geometry version 9i and version 10g Beta 2 (in the context of ArcGIS 8.3), Delft 2003, 20 p. (Confidential)

24. GISt Report No. 24, Stoter, J.E., 3D aspects of property transactions: Comparison of registration of 3D properties in the Netherlands and Denmark, Report on the short-term scientific mission in the CIST – G9 framework at the Department of Development and Planning, Center of 3D geo-information, Aalborg, Denmark, Delft 2003, 22 p.

25. GISt Report No. 25, Verbree, E., Comparison Gridding with ArcGIS 8.2 versus CPS/3, Report to Shell International Exploration and Production B.V., Delft 2004, 14 p. (confidential).

26. GISt Report No. 26, Penninga, F., Oracle 10g Topology, Testing Oracle 10g Topology with cadastral data, Delft 2004, 48 p.

27. GISt Report No. 27, Penninga, F., 3D Topography, Realization of a three dimensional topographic terrain representation in a feature-based integrated TIN/TEN model, Delft 2004, 27 p.

28. GISt Report No. 28, Penninga, F., Kartografische hoogtevoorstelling binnen TOP10NL, Inventarisatie mogelijkheden op basis van TOP10NL uitgebreid met een Digitaal Hoogtemodel, Delft 2004, 29 p.
29. GISt Report No. 29, Verbree, E. en S.Zlatanova, 3D-Modeling with respect to boundary representations within geo-DBMS, Delft 2004, 30 p.
30. GISt Report No. 30, Penninga, F., Introductie van de 3e dimensie in de TOP10NL; Voorstel voor een onderzoekstraject naar het stapsgewijs introduceren van 3D data in de TOP10NL, Delft 2005, 25 p.
31. GISt Report No. 31, P. van Asperen, M. Grothe, S. Zlatanova, M. de Vries, T. Tijssen, P. van Oosterom and A. Kabamba, Specificatie datamodel Beheerkaart Nat, RWS-AGI report/GIST Report, Delft, 2005, 130 p.
32. GISt Report No. 32, E.M. Fendel, Looking back at Gi4DM, Delft 2005, 22 p.
33. GISt Report No. 33, P. van Oosterom, T. Tijssen and F. Penninga, Topology Storage and the Use in the context of consistent data management, Delft 2005, 35 p.
34. GISt Report No. 34, E. Verbree en F. Penninga, RGI 3D Topo - DP 1-1, Inventarisatie huidige toegankelijkheid, gebruik en mogelijke toepassingen 3D topografische informatie en systemen, 3D Topo Report No. RGI-011-01/GISt Report No. 34, Delft -2005, 29 p.
35. GISt Report No. 35, E. Verbree, F. Penninga en S. Zlatanova, Datamodellering en datastructurering voor 3D topografie, 3D Topo Report No. RGI-011-02/GISt Report No. 35, Delft 2005, 44 p.
36. GISt Report No. 36, W. Looijen, M. Uitentuis en P. Bange, RGI-026: LBS-24-7, Tussenrapportage DP-1: Gebruikerswensen LBS onder redactie van E. Verbree en E. Fendel, RGI LBS-026-01/GISt Rapport No. 36, Delft 2005, 21 p.
37. GISt Report No. 37, C. van Strien, W. Looijen, P. Bange, A. Wilcsinszky, J. Steenbruggen en E. Verbree, RGI-026: LBS-24-7, Tussenrapportage DP-2: Inventarisatie geo-informatie en -services onder redactie van E. Verbree en E. Fendel, RGI LBS-026-02/GISt Rapport No. 37, Delft 2005, 21 p.
38. GISt Report No. 38, E. Verbree, S. Zlatanova en E. Wisse, RGI-026: LBS-24-7, Tussenrapportage DP-3: Specifieke wensen en eisen op het gebied van plaatsbepaling, privacy en beeldvorming, onder redactie van E. Verbree en E. Fendel, RGI LBS-026-03/GISt Rapport No. 38, Delft 2005, 15 p.
39. GISt Report No. 39, E. Verbree, E. Fendel, M. Uitentuis, P. Bange, W. Looijen, C. van Strien, E. Wisse en A. Wilcsinszky en E. Verbree, RGI-026: LBS-24-7, Eindrapportage DP-4: Workshop 28-07-2005 Geo-informatie voor politie, brandweer en hulpverlening ter plaatse, RGI LBS-026-04/GISt Rapport No. 39, Delft 2005, 18 p.
40. GISt Report No. 40, P.J.M. van Oosterom, F. Penninga and M.E. de Vries, Trendrapport GIS, GISt Report No. 40 / RWS Report AGI-2005-GAB-01, Delft, 2005, 48 p.
41. GISt Report No. 41, R. Thompson, Proof of Assertions in the Investigation of the Regular Polytope, GISt Report No. 41 / NRM-ISS090, Delft, 2005, 44 p.
42. GISt Report No. 42, F. Penninga and P. van Oosterom, Kabel- en leidingnetwerken in de kadastrale registratie (in Dutch) GISt Report No. 42, Delft, 2006, 38 p.
43. GISt Report No. 43, F. Penninga and P.J.M. van Oosterom, Editing Features in a TEN-based DBMS approach for 3D Topographic Data Modelling, Technical Report, Delft, 2006, 21 p.

44. GISt Report No. 44, M.E. de Vries, Open source clients voor UMN MapServer: PHP/Mapscript, JavaScript, Flash of Google (in Dutch), Delft, 2007, 13 p.
45. GISt Report No. 45, W. Tegtmeier, Harmonization of geo-information related to the lifecycle of civil engineering objects – with focus on uncertainty and quality of surveyed data and derived real world representations, Delft, 2007, 40 p.
46. GISt Report No. 46, W. Xu, Geo-information and formal semantics for disaster management, Delft, 2007, 31 p.
47. GISt Report No. 47, E. Verbree and E.M. Fendel, GIS technology - Trend Report, Delft, 2007, 30 p.
48. GISt Report No. 48, B.M. Meijers, Variable-Scale Geo-Information, Delft, 2008, 30 p.
49. GISt Report No. 48, Maja Bitenc, Kajsa Dahlberg, Fatih Doner, Bas van Goort, Kai Lin,Yi Yin, Xiaoyu Yuan and Sisi Zlatanova, Utilty Registration, Delft, 2008, 35 p.
50. GISt Report No 50, T.P.M. Tijssen en S. Zlatanova, Oracle Spatial 11g en ArcGIS 9.2 voor het beheer van puntenwolken (Confidential), Delft, 2008, 16 p.
51. GISt Report No. 51, S. Zlatanova, Geo-information for Crisis Management, Delft, 2008, 24 p.
52. GISt Report No. 52, P.J.M. van Oosterom, INSPIRE activiteiten in het jaar 2008 (partly in Dutch), Delft, 2009, 142 p.
53. GISt Report No. 53, P.J.M. van Oosterom with input of and feedback by Rod Thompson and Steve Huch (Department of Environment and Resource Management, Queensland Government), Delft, 2010, 60 p.
54. GISt Report No. 54, A. Dilo and S. Zlatanova, Data modeling for emergency response, Delft, 2010, 74 p.
55. GISt Report No. 55, Liu Liu, 3D indoor "door-to-door" navigation approach to support first responders in emergency response - PhD Research Proposal, Delft, 2011, 47 p.
56. GISt Report No. 56, Md. Nazmul Alam, Shadow effect on 3D City Modelling for Photovoltaic Cells - PhD Proposal, Delft, 2011, 39 p.
57. GISt Report No. 57, G.A.K. Arroyo Ohori, Realsing the Foundations of a Higher Dimensional GIS: A Study of Higher Dimensional Data Models, Data Structures and Operations – PhD Research Proposal, Delft, 2011, 68 p.


ZUIDPOLDER
VAN DELFGAUW
MOLENSLOOT
PARALLELWEG
POLDER