Exploring potential debris removal strategies during the earthquake response phase

An agent-based modeling approach to improve the post-earthquake emergency response in urban areas

J.J. (Julia) Mooren

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by

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Preface

As I present this master's thesis, my journey as a student at the Delft University of Technology comes to an end. Since beginning my bachelor's in Technische Bestuurskunde in 2018 at the Faculty of Technology, Policy, and Management, I have greatly enjoyed my time here. Leading to the completion of this masters thesis. The experience has been both rewarding and challenging, marking the conclusion of an important chapter in my life.

During my exchange in Lund, my interest in humanitarian logistics and disaster management deepened. As small improvements or small mistakes make significant impact, potentially saving lives. Particularly in an era where natural hazards are becoming more frequent and severe. It has been very fun exploring this interest more and being able to use this interest in the context of my own studies via complex system engineering and translating this theoretical interest into a model.

I would like to extend my sincere gratitude to my supervisors O. Kammouh, A. Verbraeck and N.C van der Wal who provided valuable guidance throughout this process.

Firstly, I want to thank Omar. Our bi-weekly meetings not only kept me on track but also challenged me to think critically and refine my work, ensuring that the project ran smoothly while encouraging me to push the boundaries of my understanding. Secondly, I would like to thank Natalie for her technical support, particularly with NetLogo. Her insights helped me when I was stuck and guided me to better define the scope of my research. I am also grateful to Alexander for his clear and direct feedback, which helped me make crucial decisions during the research process. His advice was instrumental in shaping the direction of this thesis.

Finally, I want to express appreciation to my friends, family, and boyfriend, who have been constant sources of support and patience. They have endured countless conversations about the challenges of modeling earthquake response, and their encouragement has meant the world to me.

I have put a great deal of energy, effort, and enthusiasm into this thesis, and I hope you find as much value in reading it as I did in creating it.

J.J. (Julia) Mooren
Delft, November 2024

Executive summary

Natural hazards can have an immense impact on peoples lives in multiple ways. Earthquakes are one of the most well-known and commonly occurring disaster on the planted and history shows that earthquakes are one of the deadliest disasters to affect humans. In urban areas, earthquakes cause significant damage, particularly in highly populated areas, leading to blocked roads and many injured residents resulting in different complex emergency response challenges.

One critical aspect of emergency response often overlooked is debris removal during the initial response phase, which are the first few days after an earthquake strikes. While debris management is typically treated as a recovery activity, its immediate integration could improve access to affected individuals, enabling faster medical care. When debris removal problems are researched, most studies focus on network recovery or use overly simplified networks and do not focus on the impact debris removal this network recovery can have on the medical assistance of injured residents in the aftermath of an earthquake. The main research question addressed is:

What is the influence of various debris removal strategies on the effectiveness of post-earthquake emergency response in urban areas?

The system studied is an urban earthquake response system consisting of several actors of which the main ones are: emergency services, local authorities, NGOs, and the local community. Debris removal plays a vital role in clearing pathways for ambulances and other emergency vehicles. In this study, an Agent-Based Model was developed to simulate casualty transportation and debris removal operations at the urban scale. The model is a so called virtual city called *Quakecity*, of which the network and environment based on a realistic urban setting, including building damage and debris, roads, hospitals and valid injured residents distribution throughout the network. This allows for the testing of various debris clearance strategies under realistic conditions. The effectiveness of the response is measured by the number of assisted residents and the number of unreachable residents in the model, in line with findings from a literature review.

An ABM was constructed using the NetLogo simulation platform to model the earthquake response system. The model simulates interactions between different agents—residents, casualty transporters, hospitals, and debris removal vehicles. Roads are blocked by varying degrees of debris.

In the model two different strategies have been investigated, given different resource availability's. These strategies have been implemented by creating different debris removal resource distributions in different zones in the network, based on zone characteristics. In addition, a supplementary strategy was investigated to test the potential of deploying army vehicles to assist with casualty transportation. The following

- Population density: This strategy distributes the available debris removal equipment based on the population density of the zones in the network, prioritizing areas with known high population density.
- Distance to hospitals: This strategy distributes the available debris removal equipment based on te average distance of the zone from the hospitals, prioritizing areas close to the hospitals.
- Deployment of army vehicles: Supplementary strategy that adds army vehicles to perform casualty transportation allowing more resedients to be reached

Each strategy was tested under two different levels of initial damage, of which the Kobe scenario simulates the response with significantly more initial damage compared to the El Centro scenario. In addition, these strategies were tested under different levels of resource availability's for both the casualty transporters and the removal equipment.

Although increasing the ambulance capacity has more influence then clearing roads for access to casualties, the simulations showed that both debris removal strategies do significantly impacts the number of residents who can be assisted by emergency services, especially in the scenario with more initial damage. The hospital-proximity strategy proved the most effective when resources were plenty. However, when debris removal resources were limited, the differences between strategies were less pronounced, raising questions about the added value of complex strategies in low-resource scenarios. The study highlights the importance of adapting strategies based on available resources to improve emergency response. In addition this study showed that using army vehicles as casualty transporters has a significant positive effect regarding the assistance of injured people. The effect of adding a few army vehicles is similar to increasing ambulance capacity significantly, showcasing its potential for future earthquake response efforts even when other resources are constrained.

Like any model, this model does not entirely represent the system of the medical response and debris removal. However, this research makes several key contributions to the field of earthquake response and debris clearance. First, it is in line with related reserearch, showing the importance of prioritizing debris removal in areas close to critical locations, such as hospitals, to maintain access for effective emergency response. The study adds to existing models by integrating debris removal as a core component of the immediate response phase, rather than focusing solely on recovery. By highlighting the direct impact of debris clearance on saving lives and improving access to casualties, this work moves beyond traditional analyses that focus on network recovery and offers a more practical perspective on how debris management affects real-world outcomes.

Future studies could further refine the strategies for integrating debris removal into earthquake response, combine strategies for optimization, or expand the model with other critical activities part of an earthquake response, making urban areas more resilient in the face of natural disasters.

Nomenclature

Abbreviations

Abbreviation	Definition
ABM	Agent-based modeling
DMC	Disaster Managemnt Cycle
DM	Disaster Management
KPI	Key Performance Indicator

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Introduction

1.1. Societal problem

Natural hazards can have an immense impact on people's lives in multiple ways. From the year 2000 till 2012, deaths caused by natural hazards have exceeded 1.1 million and over 2.7 billion people have been affected (United Nations, 2012) and this number is still growing every year. Earthquakes are one of the most well-known and commonly occurring geophysical disasters on the planet (Sadhukan et al., 2022) and history shows that earthquakes are one of the deadliest disasters to affect mankind (Bartels & van Rooyen, 2012).

One recent event shows the devastating effects earthquakes can have, which occurred on February 6th 2023, when a big earthquake near the border between Turkey and Syria caused one of the biggest disasters in the region in recent times. Tens of thousands of people have not survived this disaster and countless people have been exposed to unforgiving circumstances (United Nations, 2023).

The threat of earthquakes is likely to increase due to of global urbanization, which leads to millions of people being subject to the threat of earthquakes (Bartels & van Rooyen, 2012). This urbanization, combined with population growth and the fact that more than half of the world's large cities with populations ranging from 2 to 15 million are located in high-risk earthquake areas (United Nations, 2012), will result in more catastrophic effects and consequences of earthquakes (Tucker et al., 1994).

Millions of earthquakes occur annually, with the majority being too minor to perceive or cause damage. Nevertheless, there are instances when more severe earthquake events occur and their effects can range from minimal to profound. These seismic events may lead to structural damage, blocked streets due to debris, injuries or sometimes even loss of life ("Earthqacke Hazard & Risk across Europa", 2021).

As it is proven that the effects of earthquakes can be immense, it is very important to reduce the risks. As the event of an earthquake is nearly impossible to predict and seismologists remain unable to do so with accurate results (Rundle et al., 2021), it is impossible to know precisely when to be most prepared. However, effective risk mitigation measures and strategies can significantly reduce the impact of an earthquake when it does strike an area ("Earthqacke Hazard & Risk across Europa", 2021). Furthermore, enhanced resilience allows for better anticipation to reduce disaster losses (Cutter et al., 2013).

Besides the immense impact earthquakes have on people and their health, earthquakes also damage road networks, which hampers emergency activities during the immediate response. For example, during the 2015 earthquake in Nepal, almost 500,000 buildings were completely damaged, creating major amounts of debris that ended up on the transportation network, hindering the medical and search-and-rescue response activities (ICIMOD, 2015). Being able to reach residents quickly during an earthquake response is crucial for saving lives and minimizing harm. Immediate access ensures that critically injured individuals receive timely medical attention, reducing mortality and long-term complications. This clearly highlights the importance of making roads accessible during the immediate response in the context of disaster management. This is especially critical in urbanized areas, where the consequences of an earthquake can be significantly more severe due to higher population density and infrastructure complexity. As Duzgun et al. (2011) points out, ”major disasters in urban areas have stimulated a demand for in-depth evaluation of possible strategies to manage the large-scale damaging effects of earthquakes.”

1.2. Literature review

This section presents a review of the literature addressing the challenges of debris management during earthquake response in urban areas, followed by an overview of existing models for earthquake response and debris removal.

1.2.1. The challenge of debris in earthquake response

Disaster management and emergency response are complex processes in which a lot of challenges appear. Since any disaster relief operation is very context-specific and dynamic, the challenges involved differ based on the type, intensity, location and timing of the disaster at hand (Kovacs & Moshtari, 2019).

Within urban areas, as there are many buildings and infrastructures, debris causes a big challenge. Debris can make it very hard for rescuers and emergency services to reach survivors. Poor management of this debris, on the contrary, can cause hindrance to the social and economic recovery of the impacted area. So proper removal of debris has significant importance since it blocks the roads and prohibits emergency aid teams from accessing the disaster-affected areas. Effective debris management remains a major challenge in both the immediate rescue operations as well as the long term recovery following such disastrous event (Upadhyay & Ranjitkar, 2015). Debris clearance is a crucial task in the post-earthquake scenario, but also very difficult and complex. This is showcased by experiences from past disasters. For example, the 2015 earthquake in Nepal, in which a total of 491,620 buildings were fully damaged, 269,653 buildings partially destroyed, and 7,532 schools and 1,100 health facilities damaged (ICIMOD, 2015), creating a lot of debris on crucial parts of the transportation network, making it very difficult to deploy search and rescue operations in the immediate response. This research also showed that 4 months after the earthquake, debris has yet to be removed from certain areas, leaving people unable to return to their homes (Upadhyay & Ranjitkar, 2015). Challenges related to debris and its effect on transportation were also present in the 2017 earthquake in Iran. Roads and bridges were severely damaged, creating big congestion on roads (Maghsoudi & Moshtari, 2021), and quick damage and loss assessment tools were not present, making emergency response very difficult (Upadhyay & Ranjitkar, 2015). Other challenges regarding debris removal are discussed by Mavroulis et al. (2023). They discuss hazards encountered during debris removal, from initial phases to sorting and disposal. They highlight the environmental impact of unregulated debris disposal on sensitive habitats and propose measures to mitigate negative impacts on individuals, including workers, volunteers, and local communities, as well as the natural environment.

1.2.2. Modeling earthquake response

Challenges present in disaster management and earthquake response clarify the complicated nature of the response phase after a disaster event. Improving this process in that regards is not an easy task, as uncertainty, damage and chaos are a big part of this. However, research has been conducted on simulating different aspects of earthquake emergency response. Most literature in this field aims to support the decision-making process of policymakers in evacuation policy and urban planning, as the research helps understand the effects of disasters and earthquakes.

Much research has been conducted on improving disaster and earthquake response by improving the medical response and evacuation. Wang et al. (2012) evaluated many evacuation strategies by simulating the emergency medical response to a mass casualty even in urban areas. Battegazzorre et al. (2021) simulated an urban scale area during an earthquake response, simulating the community evacuation to hospitals. These studies do not include debris removal in their studies. Sharif et al. (2023) did incorporate debris clearance in their study on agent collaboration during the response to an earthquake. They highlight the importance of collaboration during crucial activities during the response phase and found that volunteer organizations perform most debris removal operations and if they are incapacitated, a big delay will appear in debris removal operations. However, these studies do not include debris removal as a possible factor that can improve the number of casualties that can be assisted in disaster-stricken areas.

1.2.3. Debris removal models

Even though the challenges posed by debris in carrying out an earthquake response in urban areas are well acknowledged, research on debris removal has primarily focused on the recovery and reconstruction phases (Berktaş et al., 2016), where cleanup activities are typically categorized. In disaster management literature, emergency rescue and medical care are often associated with the response phase (Altay & Green, 2006), while debris removal is considered part of the recovery phase. However, some have also focused on debris removal in the the response phase.

Some consider only building collapse modeling and blockage probability without a recovery plan. In this regard, Domaneschi et al. (2019) created a methodology to assess the area covered by debris as a result of the collapse or damage of masonry buildings. Adding to this, Lu et al. (2019) created a framework in which not only the falling debris is predicted, but also the influence of this debris on pedestrian movement is modelled. This research shows that the existence of debris has a significant influence on the total evacuation time. This research also shows the possibility of calculating debris distribution and can identify roads with a high risk of falling debris.

FEMA (2007) have provided guidelines related to post-disaster debris management outlining the activities and resources as well as describing responsibilities. However, this approach is very descriptive. Especially for debris clearance, which is phase 1, it lacks guidance on prioritizing roads or areas in the struck area in a systematic way. Some have taken this lack to create mathematical models, in which usually network blocking simulation is used that considers network recovery. These studies usually select random roads to be blocked. In this regard, Berktaş et al. (2016) created a mathematical model that aims to minimize the total time spent to reach all the critical nodes. They also created a model that minimizes the weighted sum of visiting times where weights indicate the priorities of critical nodes. Both models focus on the response phase and are applied to small provinces. Özdamar et al. (2014) focus on the coordination of debris removal operations in post-disaster environments, analyzing both deterministic and probabilistic cleanup times. Their study emphasizes two goals: maximizing network accessibility during debris clearance and minimizing the total time needed for cleanup. Çelik et al. (2015) aims to maximise flow from supply to demand nodes considering using a theoretical blockage percentage in a small neighbourhood. Lastly, Koch et al. (2020) simulated ambulance response time under various scenarios in which some roads are blocked, however not within the aftermath of an earthquake but on regular days.

Sahin et al. (2016) combined debris prediction with network recovery and focused on providing emergency relief supplies to the affected regions as soon as possible by unblocking roads by removing the accumulated debris, using a case study area in Turkey with a simplified.

1.3. Knowledge gap and research questions

Researchers commonly divide the network recovery and restoration into two phases: Phase 1 focuses on short-term repair that includes unblocking roads and repairing impassible roads and bridges to an operational, although minimal, state (Çelik et al., 2015). These activities contribute towards enabling emergency activities to resume.

From the literature, several key gaps have been identified. First, the integration of debris removal into the emergency response phase is not commonly explored. Although debris clearance plays a critical role in enabling faster emergency response, particularly in terms of reaching casualties and restoring transportation networks, it is often overlooked or relegated to the recovery phase. When the focus lies on debris removal, most studies use mathematical models and do not combine this debris removal with other response activities and solely focus on network recovery. Secondly, there is a lack of focus on addressing emergency response at the urban scale. Many studies concentrate on smaller areas and use random blockage percentages not related to debris predictions.

These research gaps result in the following research objective: To explore various debris removal strategies during phase 1, assessing their influence on the effectiveness of of an earthquake emergency response in urban areas. Thereby, this thesis will aim to contribute towards a more effective and efficient immediate response following the event of an earthquake.

This thesis sets out to address this research gap by answering the following main research question:

What is the influence of various debris removal strategies on the effectiveness of post-earthquake emergency response in urban areas?

And the following sub-questions, which will aid in answering the main research question:

1: What is the current system environment for earthquake emergency response in urban areas?
2: How can the effectiveness of an earthquake emergency response be measured in urban settings?
3: How can the dynamics of an earthquake emergency response be conceptualized and formalized for simulation purposes?
4: What are some potential debris removal strategies and to what extend can these strategies enhance the effectiveness of an earthquake emergency response in urban areas?

1.4. Research approach

There is a lack of exploration of different debris removal strategies for earthquake response in a fully urbanized environment, which led to the knowledge gap being addressed in this research. The knowledge gap results in the exploratory nature of the research. One can look at the earthquake emergency response in urban areas as a dynamic complex socio-technical system. With this in mind, system research can be conducted in various ways. Figure 1.1 shows these ways (Eduard & Ming, 2010).

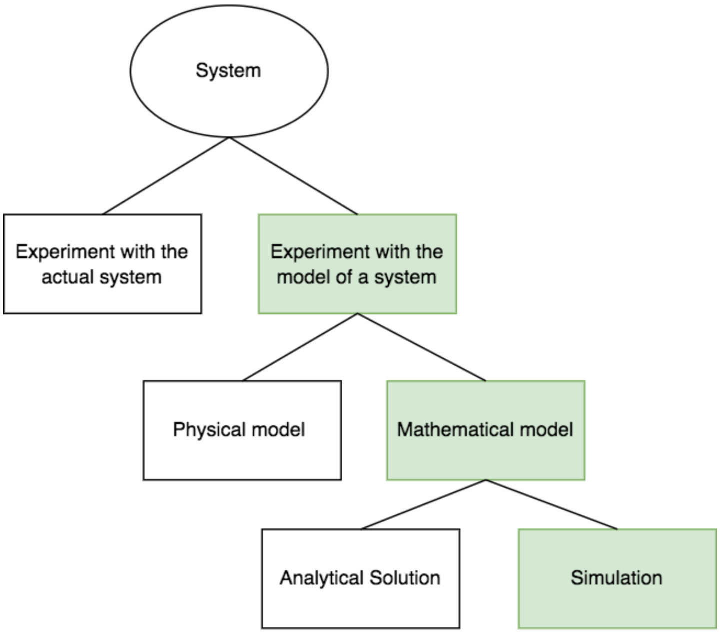


Figure 1.1: Ways to study a system (Eduard & Ming, 2010)

Due to the fact the system is created by a natural disaster and depends on many uncertain factors that relate to this disaster, it is impossible to experiment with the actual system. Therefore, this research will use a modeling approach to study the system. For the same reasons, physical models are not an option in this research, which results in the use of mathematical model. The knowledge gap reflects a lack of understanding of the effects of various strategies, which results in the choice for simulation of the model. Using this approach allows for exploration of the effects of various strategies on the behavior of the system as a whole, but also allows for analyzing relations among variables. Moreover, using this approach can create insight into how these strategies influence the effectiveness of the initial response. Then the model can be used to explore different strategies, measured by predefined Key Performance Indicators (KPIs).

The modeling approach allows for the building of a simplified version of the real world, enabling testing of various strategies under different scenarios, which is a great advantage of this approach regarding the aim of this study. Furthermore, modeling allows for ”what-if” questions to be tested (Queirós et al., 2017) and can compress or expand time to investigate the system thoroughly (Banks, 1999). However, this approach also has some limitations. One of the main challenges lies in ensuring that the model reflects the real world accurately. In this regard Podnieks (2010) states that ”There are systems that can’t be modeled in full detail even in principle”. Moreover, although models involve simplification and assumptions to make analysis more manageable, the results can be affected by this leading to inaccurate results. Therefore, consideration must be given to selecting the appropriate elements to include in the model.

1.5. Thesis outline

This thesis is divided into 9 chapters, with the first serving as the introduction. Chapter 2 introduces the research design, focusing on agent-based modeling and the overall methodology. Chapter 3 provides relevant background and a system description of earthquake response in urban areas. Chapter 4 presents a literature review on effectiveness measures in existing emergency response literature. Chapter 5 focuses on the development of the Agent-based model, while Chapter 6 explains its formalization and the implementation of the model into Netlogo and is finalized by introducing the experimental design. Chapter 7 outlines the results from the simulations, exploring the impact of debris removal strategies. Chapter 8 discusses the findings and limitations, and Chapter 9 concludes the study, offering key insights and recommendations for future research.

2

Methodology

This section will provide the methodology used in this thesis to answer the research questions. First, agent-based modeling is introduced. Additionally, the research framework is explained and the use of a virtual city is explained. Lastly, the scope of the study is set.

2.1. Agent-based modeling

Multiple modeling approaches can be used for simulation, including discrete event simulation, agent-based modeling and system dynamic modeling. ABM can be generated from the actions and interactions of multi-agent system, instead of describing an overall global phenomenon. This bottom-up approach is one of the most important features of ABM. For these reasons, ABM is particularly suitable for the analysis of complex adaptive systems and emergent phenomena (van Dam et al., 2012) (Klügl & Bazzan, 2012). Because the system at hand can be categorized as a complex adaptive system, ABM is found to be the appropriate method in this research. ABM simulation has already been used in many research areas, including the area of natural disasters. ABM allows modelers to create a computer representation of dynamic events (Mustapha et al., 2013), of which simulating the emergency response after an earthquake is a great example.

In this research, it is chosen to make use of the Netlogo software for model implementation. Netlogo is a programming language that is very useful for modeling complex systems that evolve over time. This program is mainly chosen due to the author's past experience of using Netlogo in courses. In addition, NetLogo requires less knowledge of programming language. Furthermore, Netlogo has extensive built-in capabilities, documentation, good tutorials and a large library with existing models (Klügl & Bazzan, 2012). This creates a very user-friendly environment which enhances the decision of using Netlogo as the software.

For this research the framework of Van Dam et al. (2013) is used. The framework consists of ten steps to create and use an agent-based model of a socio-technical system. These steps create a guideline throughout the whole research. This research framework can be elaborated in the following processes:

2.1.1. Problem formulation and actor identification

A literature review is conducted at the beginning of the research to identify several research gaps within earthquake emergency response literature. This led to the formulation of the research questions and the selection of the research approach.

2.1.2. System identification and decomposition

The system is identified and decomposed by using a clear scope in this research, which is described in section 2.3. The different system elements and characteristics are identified in the system description, based on available literature. This system identification mainly focused on the unique characteristics of the impact earthquakes have in urban areas as well as how casualty transportation is performed in urban areas by analysing other earthquake response events. This system analysis can be found in Chapter 3.

2.1.3. Concept formalisation

Using the output of the system identification step, a conceptual model is constructed through a series of flow diagrams that show the interaction within the system and how different elements of the model make a decision each time step. These flow diagrams are detailed and explained in Chapter 5.

2.1.4. Model formalisation

This step translates the conceptual models into a formal model by an iterative process. This formalisation gives input to all processes and variables created in the conceptual model. An overview of the variables and their input values can be found in Appendix C. The formalisation of the model has been influenced by the existence of a data set containing thorough calculations on the damage state, blocked roads and injured residents under certain seismic scenarios in the research area. These data sets are analyzed and adjusted to suit the goal of this research accordingly.

2.1.5. Software implementation

In this step, the formal model is translated into the actual model using Netlogo 6.3.0. NetLogo is a programming language that is suited for education and research and is especially useful for modeling complex systems that evolve over time. This software implementation is an iterative process in which verification is constantly performed.

2.1.6. Model verification

Model verification ensures that the model is correct and performs as intended. Verification has been performed throughout the whole modeling phase. A more detailed description of this process can be found in chapter 6 and examples can be found in Appendix E

2.1.7. Experimentation

Within this step, the experiments focused on testing two debris removal resource distribution strategies and one additional strategy, which is the deployment of army vehicles as additional casualty transporters. The model was run to analyse the impact of the strategies on the emergency response. A detailed description of the experimental campaign can be found in Chapter 6.

2.1.8. Data analysis

The results from the experimental design are presented and discussed in chapter 7, which ultimately lead to answering sub-question 4. The analysis first focuses on the influence of 2 debris removal strategies under two resource availability's, which is the distribution of debris removal resources throughout the model, based on two different characteristics of the areas in the model. Secondly, the analysis focuses on an alternative strategy, which it the introduction of a different kind of casualty transporting vehicle into the model. The performance of all experiments is measured by the number of assisted residents in the model and the number of unreachable residents for emergency services.

2.1.9. Model validation

Model validation refers to the process of making sure that the functioning of the model matches the functioning of the real system. As the earthquake response system is very case-dependent, validation is hard. However, a sensitivity analysis has been performed to increase the validity of the model. Furthermore, the trends in the model are reflected against real-world examples, rather than the specific outcomes of the model. This can be found in Chapter 6.

2.1.10. Research flow diagram

Figure 2.1 shows a diagram with the structure of the research. The structuring process was based on the previously mentioned steps. The diagram shows relationships between the different elements of the study. Besides, this figure shows where in the research the proposed sub-questions are answered.

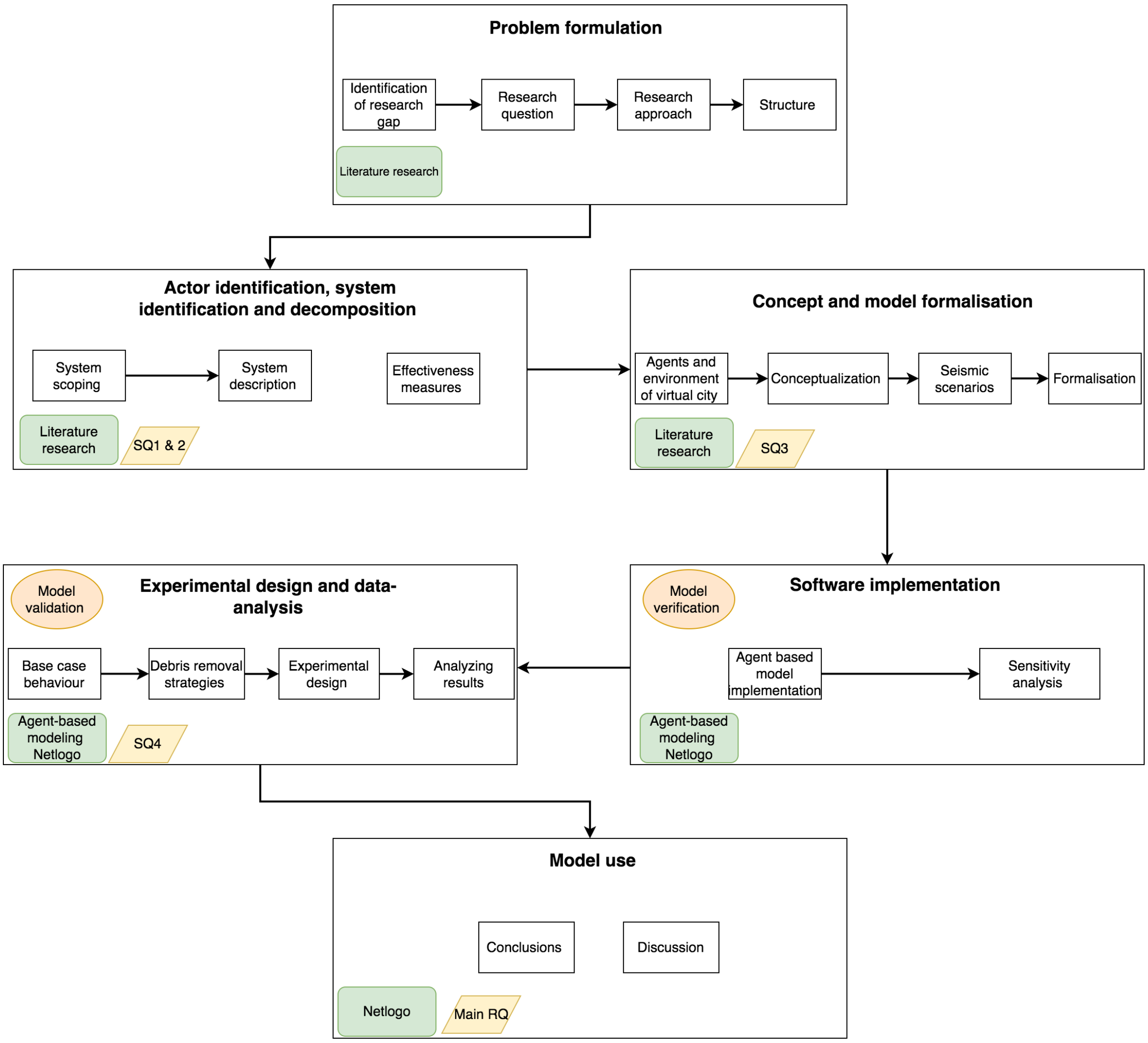


Figure 2.1: Research flow diagram

2.2. Use of a virtual city

In order to answer the main research question, it is important to capture the response environment including the dense road network that are part of an urban area as well as the response procedures in place. It has been chosen to apply modeling and simulation like explained in chapter 1. To create a realistic model environment, it has been chosen to use the urban characteristics of the area of Turin. This area is used as the base to create the virtual city, in which the strategies can be evaluated.

Turin is located in the north-west of Italy and is the capital of the Piedmont Region. Turin has been used as a great example of an urban area in other studies in a variety of research fields, like air quality (Calori et al., 2006), traffic simulation (Rapelli et al., 2021) and modeling demand for electric vehicles (Sica & Deflorio, 2023). Research conducted by Marasco et al. (2021) is considered super relevant as support for this thesis. Marasco et al. (2021) used Turin as a reference area to create a virtual city to evaluate different earthquake scenarios. From this specific research, the city network, building portfolio, calculations on injured people under different earthquake scenarios are used as a starting point in this research for creating the final model and calculations. This existing data allows this research to focus more on the impact of different strategies, rather then focusing on the specific calculation for the effects of earthquakes. Because we know that highly important factors of the system like debris and damage are calculated in a proper way, decreasing the assumptions that need to be made in this regard. This data however is first analyzed and modified before it can be used in the model, which is explained in more detail in in chapter 6.

The topology of Turin has shown to be a great example case of an urban area in a variety of research fields. Furthermore, extensive data is already available from research of Marasco et al. (2021), which can assist with setting up the model. Combined, these factors make the city of Turin very suitable for the aim of this thesis. Throughout this research, this virtual city is referred to as *QuakeCity*. It is important to note that the procedures and topology are used to base the model with the aim of creating a realistic virtual city, meaning this area is not used as a case study.

Like mentioned, Marasco et al. (2021) has performed thorough calculations of the building network of Turin under different benchmark scenarios, which are used to create the initial setup for the ABM model. These calculation combine the building network and the effect the damage has on the road network and injured people within the network. This approach is visualized in Figure 2.2.

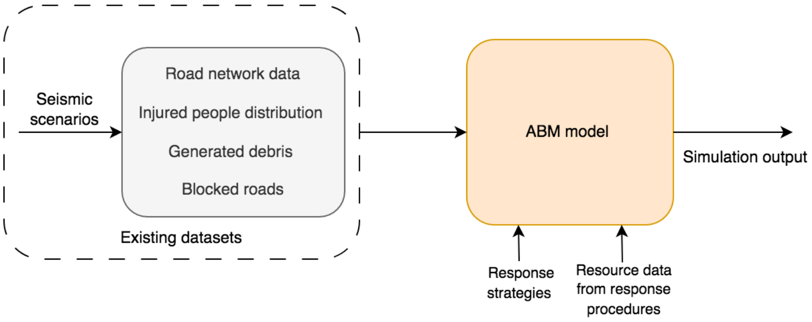


Figure 2.2: Block diagram

2.3. Research scope

Disaster response is a highly complex system which is affected by various factors. In order to achieve the research objective, it is very important to consider the scope of the research.

This thesis will focus on specific natural sudden-onset disasters, which are earthquakes. Besides, the scope will lie in the modeling of the post-earthquake response phase, eliminating the other phases that are part of the disaster management cycle (DCM). This thesis aims to improve the effectiveness of an emergency response in urban areas, rather than metropolitan areas. A metropolitan area includes not only the urban area, but also satellite cities plus intervening rural land that is socio-economically connected to the urban core city. To reduce complexity, the focus lies on urban areas.

Emergency response in this thesis is defined by the process of transportation of casualties from the disaster site to the hospitals. This means other activities that are part of a response effort like distribution of relief items, humanitarian supply chains and other response activities are outside the scope of this research.

Like introduced in section 2.2, *Quakecity* represents an urban area during an emergency response, of which the topography and building stock of the city of Turin, Italy is used. Using *Quakecity* allows to model the transportation of casualties and test the influence of various debris removal strategies. These debris removal strategies focus on resource distribution in phase 1. The aim of phase 1 is to clear debris from evacuation routes and other important paths. In Phase 2, all other debris is collected, reduced, transported, stored, recycled and disposed. This phase could take months or even years. (Özdamar et al., 2014).

3

Background

This chapter will introduce some relevant background information on disasters, the disaster management cycle (DMC) and the characteristics of an earthquake response. Thereafter this chapter zooms into debris removal and casualty transportation during earthquake response and provides an overview of the current system environment considering the scope of this thesis and thereby providing an answer to sub-question 1:

What is the current system environment for earthquake emergency response in urban areas?

3.1. Background

This section will provide relevant background information on disasters, the DMC and the activities that are part of an earthquake response. This shows the dynamics of an earthquake response.

3.1.1. Disasters

van Wassenhove (2006) identified four types of disasters based on their speed and on their cause. The speed of a disaster is either sudden-onset or slow-onset. The cause of an disaster can either be natural or human-aided. This results in the following classification shown in Figure 3.1.

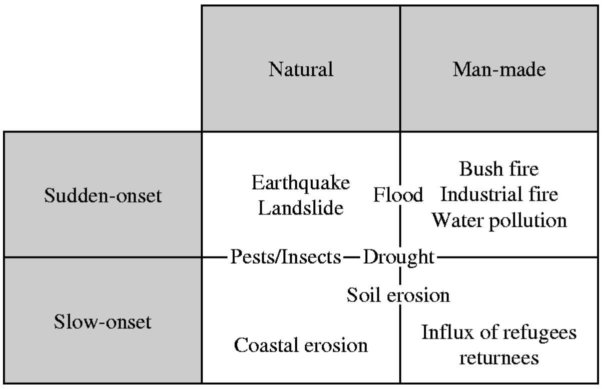


Figure 3.1: Classification of disasters

This research will focus on the classification of natural sudden-onset disasters. However, in recent times, the term natural disaster has been criticized as there are only natural hazards that can lead to a disaster. Therefore, the term disaster refers to a situation that is caused by a natural hazard. Thus, disasters can be defined as a catastrophic event that occurs as a result of a natural hazard. These hazards are large-scale geological or meteorological events and are uncontrollable and unpredictable (Salam & Khan, 2020). These include: Earthquakes, hurricanes, tornadoes, floods, wildfires, droughts, volcanic eruptions and landslides. These are threatening events, causing harm to both the physical and the social environment in which they occur. This harm is not limited to the moment of the event, but extends over the long term due to their consequences (Alcántara-Ayala, 2002). Negative results of these natural on-set disasters often include fatalities, disease, homelessness and economic losses (Salam & Khan, 2020).

3.1.2. Disaster management cycle

Disaster management can be broken down into four phases that combined form the DMC. These phases can be considered cyclical and overlapping (Kovács & Spens, 2009). These phases are: The mitigation phase, the preparedness phase, the response phase and the recovery phase.

Pre-disaster activities take place in the mitigation an preparedness phase, while post-disaster activities are included in the response and recovery phase (Carter, 2008). All these phases combined contribute to managing a disaster and therefore also reduce the risk of human and physical loss. The mitigation phase involves measures implemented both before and after a disaster aiming to reduce the effects of the disaster itself. These actions typically entail the revising of strategies, procedures, regulations and policies designed to decrease social vulnerability (Balcik et al., 2010).

The preparedness phase involves action taken before a disaster to mitigate the potential consequences and prepare relevant organization and communities by learning from the past and thereby preparing communities to respond to a disaster (Altay & Green, 2006). It is important to note that the preparedness phase encompasses activities that prepare for an effective and efficient response, distinguishing it from the mitigation phase, which focuses on the application of measures to prevent a disaster and reduce its effects.

The response phase mainly refers to activities that happen immediately after a disaster (Balcik et al., 2010) (Smet et al., 2015). Including search and rescue operations, debris removal (Oloruntoba et al., 2018), restoring essential services and infrastructures as fast as possible aimed at limiting injuries, loss of life and damage to property and the environment (National Governors' Association, 1978). It is also very important in this phase to keep assessing the disaster situation and update all involved. Thus, coordination and collaboration among the involved are crucial to have a successful response (van Wassenhove, 2006).

The recovery phase is a combination of restoration and reconstruction (Baroudi & Rapp, 2011), with the aim of restoring the situation to its original state. Thus, activities during this phase are mainly focused towards issues from a long-term perspective (Balcik et al., 2010). Figure 3.2 shows a summarized version of the DMC based on research from Tay et al. (2022) and Balcik et al. (2010).

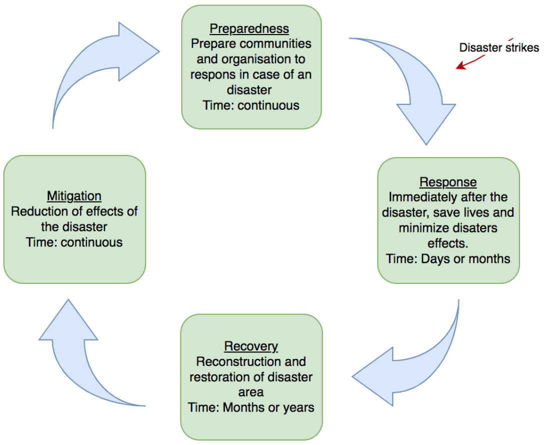


Figure 3.2: Overview of the DMC

3.1.3. Earthquake response activities

”Response” is commonly acknowledged as immediate actions to save lives, protect property, protect the environment and to meet human needs in emergency situations (Mamula-Seadon & McLean, 2015). An earthquake response consists of highly complex and intertwined activities. There are many activities that are part of an earthquake response effort in urban areas. The main activities that are crucial are the following: Search & rescue operation, casualty transportation, in-hospital response, damage assessment and repair, shelter or temporary housing, coordination and communication, logistics and resource management, community engagement and waste management.

Search and rescue operations involve the immediate deployment of emergency teams to locate, rescue, and provide initial medical treatment to survivors trapped under debris. Casualty transportation is the organized and efficient movement of injured individuals from disaster sites to medical facilities for further treatment, utilizing ambulances, emergency vehicles, and sometimes airlifts. The in-hospital response involves hospitals and medical facilities activating emergency protocols to handle the surge of patients, including triage, urgent medical treatment, surgery, and continuous care for earthquake victims. Damage assessment and repair encompass the rapid evaluation of structural damage to buildings, infrastructure, and utilities to prioritize repairs and ensure safety, addressing both immediate fixes and long-term reconstruction plans. Shelter or temporary housing is provided for those displaced by the earthquake, involving the setup of temporary facilities such as tents, modular units, or utilizing public buildings and spaces.

Coordination and communication ensure effective management of response efforts through coordinated actions among various emergency services, government agencies, and non-governmental organizations, including the dissemination of information to the public and between agencies. Logistics and resource management ensure the timely supply of necessary resources such as food, water, medical supplies, and equipment, while also managing transportation, distribution, and storage logistics. Community engagement involves local communities in the response effort, ensuring they receive accurate information and are engaged in recovery activities, including psychological support and addressing immediate human needs.

During an earthquake response, the demand for the resources to perform all of the above-mentioned activities typically exceeds the available supply, hampering emergency services.

3.2. Earthquake response system

Earthquake response has been introduced clearly in the previous section. This section will focus on the earthquake response system considered in the scope of this research. First, a brief actor analysis for the system is provided. Additionally, this section zooms in into debris removal during and casualty transportation during a response effort.

3.2.1. Actors in earthquake response

Earthquake response in urban areas is a very complex process in which a variety of actors are present. Actors in this context refer to entities, persons or organisations that can exert influence on a decision (Enserink et al., 2022). The success of the response relies heavily on the coordinated efforts of these actors to manage immediate and ongoing challenges. The actors involved can typically be grouped into four broad categories (Caglar et al., 2017):

1. Authorities
2. Non governmental organisations (NGO)
3. The local community
4. Emergency services

Each actor brings unique capabilities to the response process, contributing to various aspects. National governments and more local authorities are highly important actors in earthquake response as they develop policies that focus on prevention, risk reduction and response. Local authorities are usually responsible for deploying local emergency services and coordination of the response. NGO's can be both local, national or international. They are usually involved in different response activities, like emergency shelters, providing water and assist search and rescue activities. their initiatives usually complement the efforts of the authorities. The local community is not a single entity, but is usually a highly diverse range of social actors who can perform voluntary work during an earthquake response. Emergency services consists out of fire, rescue teams, debris management, emergency medical services and law enforcement. They are involved in tackling the emergency on-site, evacuation and communication.

Actors involved in casualty transportation

Ambulance services play a critical role as first responders, responsible for locating, stabilizing, and transporting individuals to medical facilities. Their primary goal is to ensure that casualties receive timely medical care, often navigating blocked roads and coordinating with other actors to access hard-to-reach areas. Hospitals serve as the main destination for casualties, where their key responsibility is to triage and treat incoming patients. Hospitals must rapidly expand capacity, often establishing temporary triage centres, to handle the influx of casualties and work closely with ambulance services to prioritize severe cases (World Health Organization, 2007). Local authorities are responsible for the overall coordination of emergency response, including casualty transportation. Their goal is to facilitate efficient transport by managing traffic control. In large-scale disasters, the military sometimes provides crucial logistical support, particularly when civilian resources are overwhelmed. While the military's primary role is often focused on logistical support, such as distributing supplies, clearing debris, and restoring critical infrastructure, there is potential for using military vehicles to support casualty transportation.

Actors involved in debris removal

Debris removal management teams play a vital role in coordinating and overseeing the entire debris clearance process. These teams are responsible for assessing the scale of the debris, developing a debris removal plan, and prioritizing areas for clearance to ensure that critical infrastructure and transportation routes are quickly restored (FEMA, 2007). Their primary goal is to ensure the safe and efficient removal of debris to enable emergency services and civilian movement across the affected areas. Contractors are typically hired to carry out the physical removal of debris (FEMA, 2007). Local authorities are responsible for the overall coordination of debris removal operations, ensuring that resources are allocated efficiently and that debris clearance is aligned with broader emergency response goals. Through close coordination with contractors and debris management teams, local authorities aim to restore public order and ensure the safe movement of people and resources throughout the urban environment.

3.2.2. Earthquake response in urban areas

An earthquake response varies significantly across different regions and urban settings. The way an earthquake response is set up is influenced by many factors. This section will highlight the unique characteristics of an earthquake response in urban areas.

Earthquakes can strike all throughout the world. Their effects can vary a lot depending on the location. Urban areas generally have more resources and better infrastructure compared to rural areas, which can facilitate a quicker and more organized response. Urban populations in that sense have better access to resources in the immediate aftermath (Hall et al., 2017). Larger urban areas often have specialized emergency services ready to respond to a disaster, such as an earthquake. Population density creates a big difference in earthquake responses, highly populated urban areas can cause complications during emergency efforts and increase the potential risk of casualties and damage to buildings and infrastructure. This differs a lot from for example more rural areas, where usually fewer resources are available and less robust infrastructure (Balica & Wright, 2010), which can delay response operations, whilst local emergency services can lack proper equipment and training needed for an effective earthquake response.

Another big difference in response operations is based on whether the affected area is located in a developed or developing country. In developed countries, disaster preparedness and response plans are usually in place, including public education and emergency drills. Furthermore, developed countries have more technological advances during earthquake response and have more financial resources to use during the response, but also for the recovery process. Developing countries on the other hand, usually have limited resources, both financial and material resources. In this regard, undeveloped countries rely heavily on international aid and assistance. Besides, response efforts in developing countries are frequently delayed due to a variety of factors including lack of coordination and slower mobilization of resources. Poor infrastructure and non-compliance with building codes and lack of resilient construction increase the earthquake vulnerability of developing countries often resulting in more severe damage and suffering.

3.3. Debris and Debris removal

Unfortunately, earthquakes generate enormous amounts of debris. The volume of debris highly depends on the magnitude of the earthquake, but also depends on the region in which the earthquake strikes. Table 6.5 showcases this.

Table 3.1: Amount of debris in recent earthquakes

Year	Event	Debris Amount
1999	Marmara Earthquake, Turkey	13 million tons (Baycan, 2004)
1995	Kobe Earthquake, Japan	15 million m^3 (Baycan & Petersen, 2002)
2015	Nepal earthquake	11 million m^3 (Dugar et al., 2020)
2016	Ecuador earthquake	3 million m^3 (Guerrero-Miranda & Luque González, 2021)

Earthquakes usually generate a wide range of debris, each requiring specific handling and disposal methods. The main kinds of debris are the following: Vegetative debris includes fallen trees, branches, and stumps, often cluttering public rights-of-way. Construction and demolition debris, comprising damaged building materials such as wood, drywall, glass, metal, roofing materials, and flooring, often results from the collapse of structures. Earthquakes can also deposit soil, mud, and sand, impacting streets. Besides these main types of debris, other types of debris are also there like white goods, including household appliances, general waste, chemical and biological waste (FEMA, 2007). This diversity in debris types highlights the need for a comprehensive and adaptable approach to debris management following an earthquake. In urban areas, the main type of debris is debris generated by buildings and infrastructures where there is usually more debris in the highly dense center areas. Figure 3.3 shows multiple levels of debris on roads in urban areas after an earthquake, showcasing that not all debris has to cause major issues for emergency services. However, severe debris as shown in Figure 3.3c does imply significant issues for reaching the struck area.


(a) (b) (c)

Figure 3.3: Different levels of debris in city streets

Debris removal is relevant throughout the whole disaster timeline. Çelik et al. (2015) created a framework which showcases the stages of debris removal, presented in Figure 3.4. Debris removal starts with strategies and management in the preparedness phase and ends with collecting all debris and transportation of debris from the disaster area to collection sites for further processes or final disposal. Lastly, some debris is recycled. As mentioned in 2.3, this thesis focuses on debris clearance, which is to unblock the roads by pushing the debris to the side so that search and rescue, so that relief transportation and casualty transportation can proceed as quickly as possible with the purpose of reducing the threat to life, public health and safety.

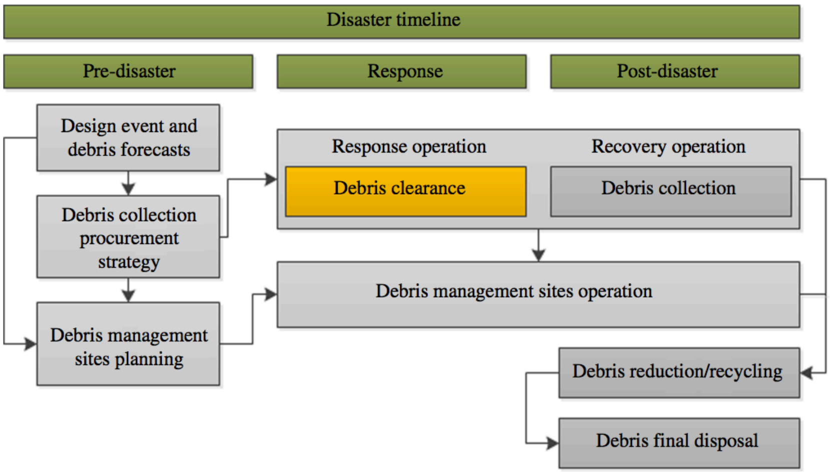


Figure 3.4: Debris operations (Çelik et al., 2015)

Various equipment can be used during debris clearance operations, ranging from hand tools like shovels and axed to heavy machinery like bulldozers, cranes and loaders (FEMA, 2007). During the response, the focus lies on clearing paths to let emergency services continue. The main equipment used are bulldozers, as these can push large amounts of debris and create clear paths through heavily affected areas. Their power and versatility make them indispensable in the initial stages of debris removal (FEMA, 2007).

Current rules and institutions regarding debris removal in disaster response are shaped by guidelines from agencies like the Federal Emergency Management Agency, local government policies, and international best practices. During the debris clearance phase, local or federal emergency management authorities typically decide which roads or areas in the struck area to prioritize (FEMA, 2007). Since the demand for resources often exceeds availability, strategically deploying debris removal teams is critical to maximizing efficiency. Unfortunately, many pre-disaster emergency plans do not include detailed strategies for debris clearance, leaving authorities to make ad-hoc decisions during a crisis (Mclean et al., 2012). When planning clearance, authorities must also consider resource limitations and tailor their choice of equipment based on the debris volume on each road (Çelik et al., 2015). Additionally, debris removal contracts usually follow competitive procurement processes to ensure transparency and cost-effectiveness, and all operations must comply with environmental laws.

Table 3.2 provides an overview of the characteristics of debris and debris removal for urban areas.

Table 3.2: Characteristics of debris in urban areas

Aspect	Urban Areas
Debris Composition	More debris from buildings and infrastructures Dense, high-rise buildings create structural debris
Debris Removal Resources	Heavy machinery is available Faster access to resources due to proximity and established supply chains
Road Infrastructure	Dense road networks but likely more road blockages from debris and areas with narrow streets

3.4. Casualty evacuation

In the aftermath of an urban earthquake, the transportation of casualties is a critical component of emergency response operations. Urban environments, characterized by their dense populations and complex infrastructure, present unique challenges in the efficient movement of injured individuals. Transporting casualties in an urban earthquake response is the transport of injured individuals from the disaster site to medical facilities efficiently and safely. This system is crucial for maximizing the survival rate and ensuring possible recovery for casualties.

Injured people are a major part of the transportation system, as they are the ones that need to be transported. During an earthquake response, injured people are usually assessed and categorized based on the severity of their injuries. This categorization helps to prioritize who needs immediate medical assistance and who can wait a bit longer. This ensures that the most critical patients are transported first (Wu et al., 2023).

Another aspect of casualty transportation are the ambulances. Ambulances generally have limited capacity, usually accommodating one and sometimes two critically injured patients at a time. This highlights the need to make efficient use of the available ambulances (Olgun & Ozcelik, 2023). During an earthquake response, not only ambulances are responsible for transporting casualties, many people either go to the hospital by themselves, or are brought to the hospital by community members. For example, during the 2011 Christchurch earthquake, within minutes injured people started to arrive at the hospital transported in various ways. Some on foot, carried by other people, in cars, in small trucks, or carried on doors (Dolan et al., 2011) (Ardagh et al., 2012). Lastly, community awareness and preparedness play vital roles in the casualty transportation system. Trained volunteers can assist in initial triage, provide first aid, and support the transportation of less critical patients, thereby allowing professional responders to focus on the most severe cases (Çağlayan & Satoglu, 2022).

Table 3.3 shows an overview of the characteristics of casualty transportation in urban areas.

Table 3.3: Aspects of casualty transportation in urban areas

Aspect	Urban areas
Access to Casualties	Faster access to casualties once roads are cleared, though blockages may initially slow response
Casualty Transportation	More ambulances and specialized emergency services available Shorter transportation times due to closer proximity to hospitals
Hospital Accessibility	Greater number of hospitals in closer proximity to affected areas Casualties have more immediate access to medical facilities
Self-Transportation	Residents more likely to use personal vehicles, bikes, or walk to hospitals once routes are clear

4

Effectiveness of emergency response

This chapter will entail a literature review that aims to gain an understanding of what effectiveness means in the context of earthquake response. Moreover, this chapter strives to find appropriate key performance indicators for the agent-based model that evaluates the different scenarios. For this literature review, first some general research has been performed on the effectiveness of earthquake response. Subsequently, multiple articles are reviewed to see how others in the research field of disaster management and earthquake response assess the effectiveness of an earthquake response. As the aim of literature in this field varies and usually different aspects of earthquakes are present, only the indicators found relevant to the aim of this research are presented in this section. Furthermore, this chapter aims to provide an answer to sub-question 2.

How can the effectiveness of an earthquake emergency response be measured in urban settings?

4.1. Effectiveness in earthquake response

According to the dictionary, effectiveness is defined as "Successful or achieving the results that you want". Response is defined by the UN as: " The provision of emergency services and public assistance during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected" (United Nations, 2009). This implies that the effectiveness of a response translates into the degree to which actions taken during and after an earthquake minimize damage, save lives, and facilitate basic needs. Effectiveness in earthquake response is thus crucial in minimizing the impact on human lives and infrastructure. It hinges on a well-coordinated effort involving accurate communication, rapid mobilization of emergency services, and implementation of predefined plans.

Effectiveness in earthquake response is a very broad concept as many factors can contribute towards an effective response. In this regard, Davidson et al. (1998) identified 12 aspects that contribute towards an effective emergency response and recovery effort. These are the following: 1) emergency management system, 2) communications, 3) financial arrangements, 4) legislation, 5) damage assessment, 6) search-and-rescue, 7) secondary hazard control, 8) health care, 9) mass care, 10) shelter, 11) clean-up, and 12) restoration services. Effectiveness in earthquake response is measured by the extent to which these elements work together to reduce the immediate impact of the earthquake, support the affected populations, and set the stage for a resilient recovery. Response is predominantly focused on the immediate response and short-term needs and so it the scope of this research, meaning the factors relating to recovery are not considered to be part of the term effectiveness in this these.

The effectiveness of the health aspect of an emergency response also contains out of many factors. Some of these components are the following: Rapid deployment of resources; on-site first side; the establishments of field hospitals; capacity and preparedness of hospitals and medical supply chain management (Perry et al., 2001).

Rapid deployment of resources includes the quick dispatch of ambulances and medical staff. Their effectiveness relies on the speed of deployment and their ability to navigate through the disaster-effected areas. Well-defined triage systems, which are protocols used in emergency situations, ensure appropriate use of of resources. Providing first-aid can significantly impact survival rates, ensuring a more effective health response. The same applies to the deployment of field hospitals. These can alleviate the burden on permanent medical facilities and enhance the capacity for providing aid which results in more people being assisted and potentially saved. Capacity and preparedness of hospitals also enhance the effectiveness of a response via well-working surge-capacity plans and adequate staffing. Besides these patient-related aspects of the medical response, communication, coordination and sufficient resources are crucial in achieving an effective response effort.

4.2. Effectiveness measurements

The previous section clarified the meaning of effectiveness in terms of general earthquake response and within the medical response. In order to translate this meaning into indicators that can be used to assess the earthquake response in a model, a literature review is performed. For this literature review, a total of ten articles have been reviewed. These articles encompass evaluations or simulations of earthquake responses. As this thesis predominantly focuses on exploring response strategies and the impact these have on the medical response, all articles included are related to the medical response. The goal of this section is thus to gain an understanding of appropriate measurements to evaluate the effectiveness of an earthquake response, acknowledging the scope of the research. This will assist in choosing the right indicators for the simulation model.

Within the scope of this research, finding measurements that relate to the effectiveness of the medical response is the most relevant. During the aftermath of disasters, including earthquakes, one of the most fundamental needs of individuals is to be provided with health care services (Samei et al., 2023). This section will discuss different studies that modeled or simulated earthquake response whilst incorporating the medical response.

Marasco et al. (2021) created a virtual city in which different earthquake scenarios are simulated. For the health and evacuation sub-model in their research, they used the number of severely injured individuals waiting to be rescued as a measure to analyze the emergency response. Sharif et al. (2023) used a similar approach, measuring the recovered population and cumulative mortality. The number of deceased citizens was also used as a performance measure by Çağlayan and Satoglu (2022). Wang et al. (2012) use the mortality amongst casualties after a mass casualty event in their research that models an emergency medical response to a mass casualty event in an urban area.

Others have created their own indicator, in this regard Kirac et al. (2024) use the critical response rate, which represents the percentage of citizens who receive assistance within the duration of the simulation. They use this metric in their model that evaluates collaborations between actors to achieve an effective response. Similarly to other studies, they also used the percentage of injured citizens as a measure. Bae et al. (2017) use the preventable death ratio, which is the fraction of expected number of death patients who would not be dead if definitive care was provided instantly.

Some use a different approach and quantify an effective outcome using response time, rather than patient outcomes. Koch et al. (2020) use the response time of ambulances, whilst (Battegazzorre et al., 2021) use the time required to bring all seriously injured to the hospital. This last metric is also used by Cimellaro et al. (2013). Golazad et al. (2024) use waiting time for patients to receive medical assistance in their integrated model to evaluate policies to enhance the healthcare response.

Regarding effectively in debris removal efforts in the response phase, measures are harder to generalise. Mainly because most research focuses on the recovery phase of debris removal. However, (Özdamar et al., 2014) use the progress of debris removal to showcase whether this activity is effective. However, this research includes the response phase as well as long-term recovery. As most research in this field are highly mathematical models, the main focus lies on optimizing network connectivity (Berktaş et al., 2016).

4.3. Conclusion

Effectiveness in earthquake response seems to fold out into the ability of emergency services to save lives, reduce health impacts and ensure public safety. This ability is hampered and impacted by many different factors and is very case dependent, as all earthquake responses tackle different problems. However, a quick response in which saving lives is a priority seems to be the main focus of an effective response.

This focus can also be found back in the literature that quantifies effectiveness in modeling and simulation. In literature evaluating earthquake responses, many different kinds of measurements and criteria are used to evaluate the effectiveness of a response effort. This is a result of the fact that many factors contribute towards an effective response effort. There do not seem to be generic metrics to use to measure response effectiveness, the metrics used highly depend on the aim of the research. However, two main approaches can be distinguished from this literature review: Patient outcomes and the metrics using some form of response time. Patient outcomes usually result in metrics related to the number of injuries, deaths or injuries resulting in death without medical assistance. The response time, although quantifiable in many ways, is a focus in many studies, meaning minimizing the time in emergency activities and thereby creating an efficient and effective response. In the literature on emergency response and debris removal, the main focus lies on optimizing network connectivity.

5

Model development

This chapter explains the model that translates the response procedures and characteristics into a conceptual model. First the conceptualization will be described for the agent-based model, in which the processes, sub-models and agents are specified. Thereby this chapter starts to to provide an answer to sub-question 3:

How can the dynamics of an earthquake emergency response be conceptualized and formalized for simulation purposes?

5.1. Agent-based-models

As mentioned in Chapter 2, the simulation method for this research is agent-based modeling using Netlogo software. Within agent-based models, there are three main components. These components are the agents, the environment and time. Agents and the environment interact over time.

Agents: Agents, also known as an entity, can be defined as an autonomous individual element with specific properties and actions (Jennings, 2000). An agent can represent both animate as inanimate objects. Typically, each agent follows a set of rules of behavior based on its characteristics and interactions with other agents in the environment.

The interactions of agents are described by a set of rules. These rules can be very simple or highly complex. They can be as simple as an ”if-then” rule or as complex as adaptive techniques (Díez-Echavarría et al., 2019). Agents can interact with each other, with other types of agents, or with the environment. According to Jennings (2000) and Van Dam et al. (2013), agents have the following characteristics:

- Agents are encapsulated, possessing distinct identities with clearly defined boundaries.
- They operate within specific environments, receive information from and react to it.
- Agents are flexible, being able to adapt to changes and proactively responding to stimulon.
- They are autonomous, exercising control over their internal states and behaviors.
- Agents are goal-oriented, striving to fulfil objectives, solve problems or achieve defined goals.

Environment: The environment in the model is defined as the place where agents are located and act (Díez-Echavarría et al., 2019). The environment is a space in which agents can interact. Besides, the environment provides the agent in the models with information. Due to the exchange of information within the environment, agents can adapt their behavior or strategies. On the other hand, the environment can also be changed by the agents.

Time: In real-life systems, agents can interact concurrently and continuously (Van Dam et al., 2013). In an agent-based model, these interactions occur in discrete time steps (Díez-Echavarría et al., 2019), constraining parallel interactions based on software and hardware capabilities.

5.2. Model purpose and requirements

The purpose of the model is to explore different debris removal strategies in the form of distributing debris removal resources and analyze their influence on the effectiveness of the medical response to an earthquake in an urban area. Thus, the base scenario of this model is the response to evacuating injured residents to the hospital and the base case includes debris removal resources that are evenly distributed. In this sense, the model at hand is an exploration model, as it tries to identify policies or strategies that positively influence the response phase. Considering the extent to which the model can capture the response phase, this model can be useful for policymakers and authorities of urban cities, as the model will help understand the response phase and might create useful insights.

Model requirements help to translate the conceptual model into an actual model. In summary, the model should:

- Focus on saving people's life and minimising the health impact
- Model the transportation of injured residents to hospitals
- Be able to apply different resource availability for casualty transportation and casualty transportation
- Allow for insight into the effects of the debris removal strategies on the transportation and reachability of injured residents

5.3. System boundary and demarcation

Models are always a simplified version of the real world and when studying a socio-technical system, it is crucial to define a clear set of boundaries. This will define the scope and limits of the model created. This step ensures a better understanding of what is being modeled and to which extent the model is able to represent reality. Three different system boundaries are discussed.

Temporal boundaries

Time is an intrinsic property of the environment where the entities in a model exist (Van Dam et al., 2013). The model is designed to simulate different aspects of an emergency response after an earthquake, with a focus on the medical response debris removal strategies. As the model focuses on the response, the earthquake event itself is outside the model scope and the simulation will start with an initial damage state including the blocked roads, injured residents and debris.

Spatial boundaries

As the area under consideration is very large, clear spatial boundaries must be set to keep the research manageable and allow the model to run smoothly, whilst being in line with the aim of the study. In short, the model represents a specific section that is based on the physical road network of the city of Turin, Italy. The roads are modeled using coordinates, and therefore the proportions in the model correspond with the real road network. The spatial boundaries, however, are limited to roads, buildings and hospitals, the specific area used in the model is elaborated on in 6.1. Furthermore, the model scope will only include pre-hospital evacuation and debris removal.

External boundaries

The model focuses on the response to an earthquake event. More specifically the focus will lie on the medical response and road clearance to reduce the impact on a community. Therefore, other activities that are part of an earthquake response are placed outside of the system. These include logistics, resource management, coordination, search and rescue and proving temporary housing. Furthermore, anything related to the cause of an earthquake event are excluded.

5.4. Conceptualization

Now that the components of an agent-based model are clarified and the boundaries are set, a conceptual model can be created. This conceptual model provides a top-level view of what is being modeled. This will be done following certain conceptualization steps. The processes that are simulated in the base model are based on those described in Chapter 3. However, due to the complexity and size of a response event, it is not possible to include all response activities in the model. Thus, simplification and choices must be made and therefore the main processes in the model are the following:

1. Casualty transportation
2. Debris removal

First the agents and their interactions are explained. Then the sub-models are model presented and thereafter, the full conceptual model is shown.

5.4.1. Agent, properties and interactions

In order to implement the agents and processes in the actual Agent-Based model, the system is divided into multiple agents and objects that interact with each other. This section will specify these elements using a Unified Modeling Language (UML) diagram. This is an approach for modeling and documenting software.

The UML diagram is constructed for the ABM model and is portrayed in Figure 5.1. It provides an overview of the different classes present in the model, what attributes they have and what operations they perform.

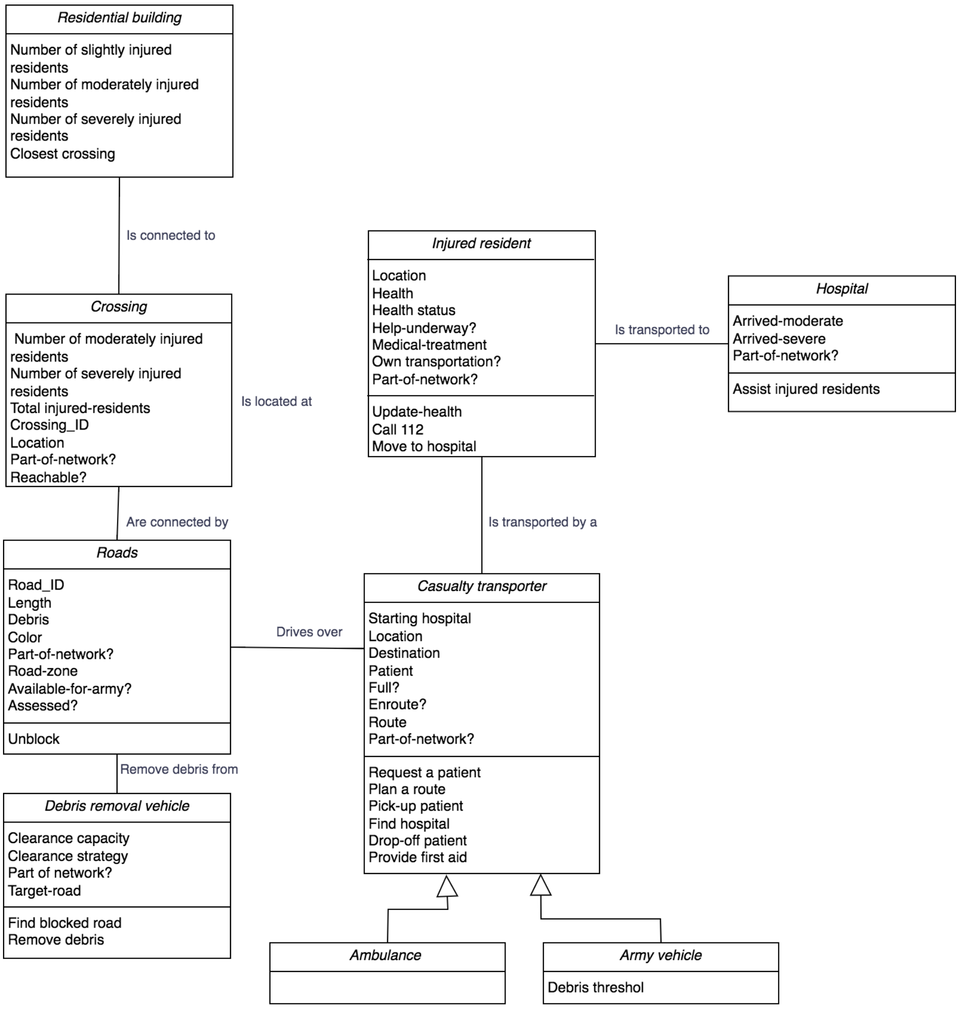


Figure 5.1: UML diagram

The main components of the model are injured residents, casualty transporters, hospitals and debris removal vehicles, whilst the environment consists of the road network. This network is internally divided into 10 city zones. The nodes represent crossings and intersections in the network, whilst the links represent the roads in the city. The residents in the model have a health status, resulting from the earthquake event and determined by the damage state of the building that they are located in. The injured residents are located on the nodes in the model. Random injured residents will call 112 to report their injuries. Depending on the environment and health status, residents either wait until they are picked up by an ambulance to be transported to a hospital, move to the hospital themselves or stay in place.

The ambulances pick up injured residents that are reported as injured and transport them to one of the hospitals in the model. They do this using accessible roads only.

The buildings in the model are either residential buildings or hospitals. The residential buildings are connected to the crossings and all injured residents from these buildings are located on the closest crossings. Hospitals are the endpoint for the ambulances, as residents who are transported to the hospital will be dropped off there.

Roads in the model are part of the network graph and they can be blocked, accessible for army vehicles or accessible for both army vehicles and ambulances. This is determined in the setup and is originally based on the amount of debris that has been created by damaged buildings. The generated debris is removed by debris removal vehicles that move the debris to the sides of the road to make the road passable for ambulances.

5.4.2. Conceptualizing the network

In disaster situations, roads are used as an evacuation route to secure the safety of the citizens, to preserve human resources, and to transport emergency supplies to and within the disaster-stricken area. A road network is the most representative geographic information of modern cities (Kim et al., 2023). The way a road network is set up also plays a key role in the decision-making process for disaster planning, and setting up disaster response. This is caused by the fact that road networks facilitate the local connectivity (Jenelius et al., 2006). The network consists out of nodes and links, which represent the intersections and roads in the transport network. Some nodes are turned into hospitals and act as the endpoint for casualty transportation. The road network is divided into 10 predefined zones, which are used to distribute the debris removal vehicles later on. The conceptualization of the network in the model is summarized in Table 5.1.

Table 5.1: Conceptualisation of network

Concept	Description
Road network	Un-directed graph based on the road network of Turin
Road	Link in in the graph based on coordinates
Crossing	Node in the graph based on coordinates
Hospital	Node of which the breed has been changed to hospital
Cityzone	Specific area of the network
Debris	Volume of debris correlated with the length of the road

5.4.3. Sub-models

The main sub-models present in the model are the following: the injured resident sub-model, the pre-hospital sub-model and the debris removal sub-model. A detailed description of the concept in the model and the behavior of the agents in these sub-models are described in this section.

Injured residents sub-model

The injured residents sub-model shows the characteristics and behavior of the injured residents. The conceptual model is shown in Figure 5.2. The concepts and a description are shown in Table 5.2.

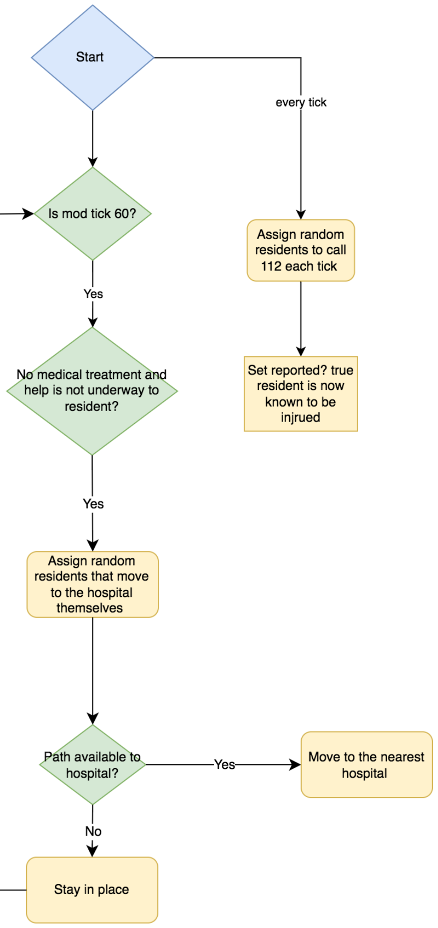


Figure 5.2: Flow diagram residents

In the model, injured residents can be in one of two health states: moderate or severe. This health status is later used in the casualty transportation sub-model to prioritize which residents ambulances should be picked up first. At each tick, random injured residents are selected to call 112 and report their injuries, making them known to the system and available for casualty transport. In the model, residents can also go to the hospital by themselves. Every hour, random residents are checked to see if they can reach the hospital independently. This is determined by checking if a clear path is available from the resident's location to the hospital, meaning no roads on the route are blocked by debris. If a viable route exists, the resident moves to the hospital.

Table 5.2: Conceptualisation of residents

Concept	Description
Resident	Entity located on a node in the network
Path	Defines whether there is a path without blocked roads to the hospital
Reported	A resident is reported and known to be injured if they have called 112
Health-status	Defines whether a resident is moderately or severely injured
Medical-treatment	Defines whether the resident is at the hospital, in the ambulance, or on their origin node
Help-underway	Defines if the resident is the target patient of an ambulance

Pre-hospital sub-model

The conceptual model is shown in Figure 5.3. This conceptual model highlights the individual behaviour of casualty transporters in the model. Thereafter the concepts within this sub-model are conceptualised and shown in Table 5.3.

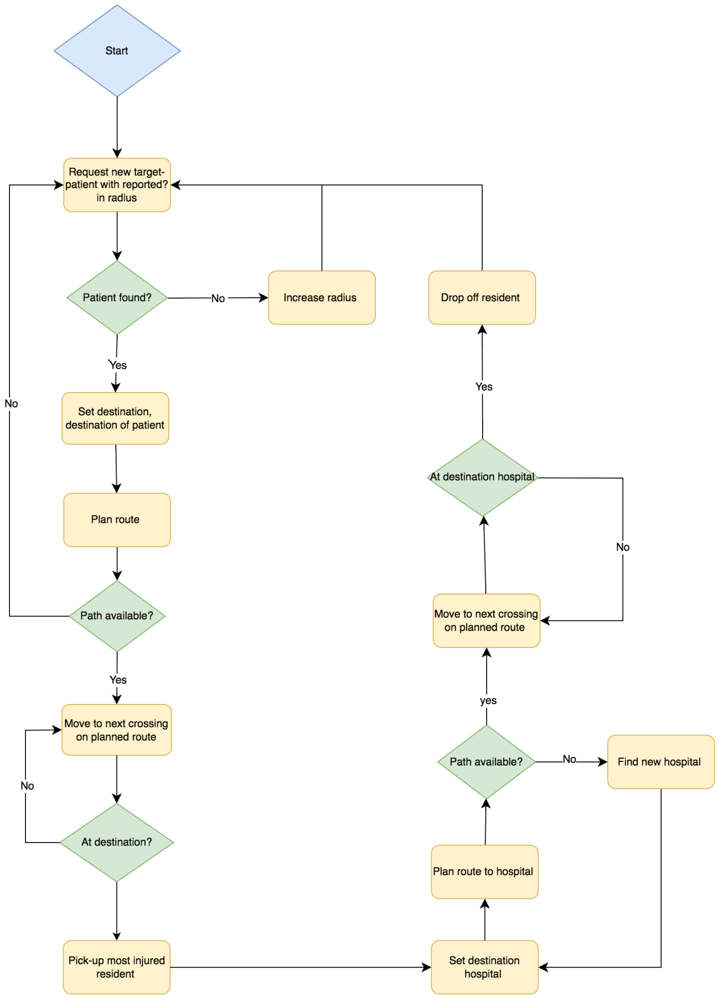


Figure 5.3: Flow diagram ambulances

Ambulances are responsible for casualty evacuation from the incident site to one of the hospitals in the model and operate throughout the whole city network. Initially, the ambulances operate in a predefined radius and they find the most-injured resident that is reported as injured in that radius. The initial tasks of the ambulance can be summarized as follows:

- Prioritize most injured resident in the radius that is known to be injured
- Make this resident the target patient
- Drive along a calculated path to the disaster site, using only non-blocked roads

Once the ambulance has a target resident, it will create a route from its location to the location of the resident, only using roads that are not blocked due to debris. This route is a sequence of nodes connected by available roads in the network. When an ambulance arrives at the site of the targeted residents the following rules are in place:

- Prioritize the most severely injured resident at that site, even if this is not the target patient
- Pick up the injured resident
- Drive along a calculated path to the nearest hospital, using only non-blocked roads
- Drop off injured resident at the hospital
- One ambulance can transport 1 resident at the time

At the site of the target patient, the ambulance checks if there is someone who is even more severely injured, that is not reported yet. This resident is then prioritized, even if this is not the same resident as the initially targeted patient. This injured resident is picked up by the ambulance. Thereafter, the ambulance will request a route to the nearest hospital. This becomes the target hospital and the ambulance will create a route to this destination using only non-blocked routes. In the model it is assumed that hospitals have unlimited capacity and is it assumed that the injured residents receive medical care once they have arrived at one of the hospitals.

Army vehicles operate using the same logic as the ambulances throughout the whole network. However, army vehicles can reach residents that are not yet reachable for ambulances. This means that whilst targeting a patient and planning a route, the route can not only go over available roads but also over blocked roads that are already accessible for army vehicles. A road is available for army vehicles once the debris on the road is below the army vehicles threshold.

Table 5.3: Conceptualisation of casualty transportation

Concept	**Description**
Route	Sequence of nodes connected by accessible roads
Search radius	Radius in which injured residents are targeted and increases when no resident is found
Target patient	Injured resident that has called 112
Destination	Node where the target patient is located
Desination hospital	Closest hospital from the injured resident

Debris removal sub-model

Whilst casualty transporters operate throughout the whole network, debris removal vehicles operate within the specified city zones. Due to no specific rules existing in most emergency plans, an assumption must be made regarding the operation of debris removal in the base scenario. Thus, it is assumed that debris removal vehicles will clear roads within the city zone that they are located in and the vehicles are evenly distributed throughout the zones in the city. However, as it is not known immediately what roads are blocked, each tick some blocked roads are assessed. Only assessed roads can be targeted to remove debris from. The conceptual model for debris removal vehicles is shown in Figure 5.4.

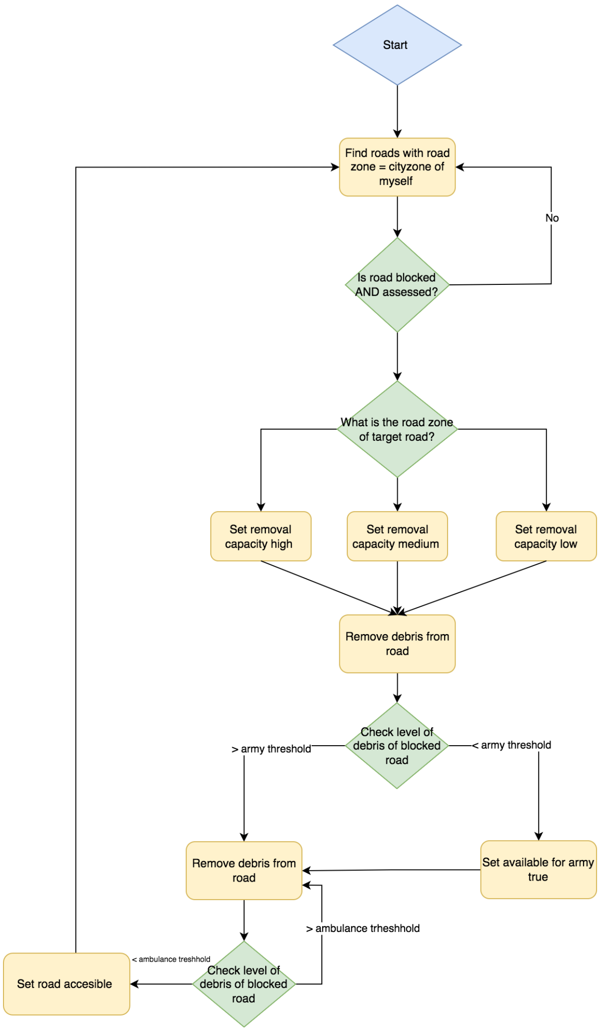


Figure 5.4: Conceptual diagram road clearance

When a debris removal vehicle is given the assignment to clear a certain road, it will check the level of debris that is located on that specific road and will start clearing the roads. Once the debris on a road is lower than the army vehicles threshold, the road can be used by these vehicles. However, the debris removal vehicle will continue to clear the roads until the threshold for ambulance accessibility is reached. The road then becomes accessible and can be used for casualty transportation by army vehicles and ambulances. After the road is accessible for ambulances, the debris removal vehicle finds a new road to clear.

This sub-model contains the following main assumptions. Debris is modeled as one type of debris and this debris can always be removed by the debris removal vehicle. Additionally, the debris dozers have a certain clearance capacity. The debris removal capacity is influenced by the population density of the zone in which the vehicles operate. Densely populated areas tend to generate more debris due to higher building concentrations and narrower streets. In line with this, these areas are likely to have a greater number of injured residents. As a result, debris removal vehicles must operate with increased caution, navigating congested spaces and managing more complex obstructions, which slows down the overall removal process. This is conceptualised by reducing the removal capacity of the debris dozers in these areas.

Table 5.4: Conceptualization of debris removal

Concept	Description
Debris dozer	Entity located on a node in a city zone
Assessed road	Road that is known to be blocked and can be targeted by the debris dozer
Ambulance threshold	Threshold for road accessibility determined by the length of the road
Army threshold	Threshold for road accessibility for army vehicles determined by the length of the road
Removal capacity	Removal capacity is based on the location of the target road, assuming debris removal from roads in more dense areas takes longer

5.4.4. Full conceptual model

The presented sub-models showcased the individual behavior in the main sub-models. However, all the components of the model also interact with each other. The full conceptual model, which also includes the residents and hospitals is shown in Figure 5.5.

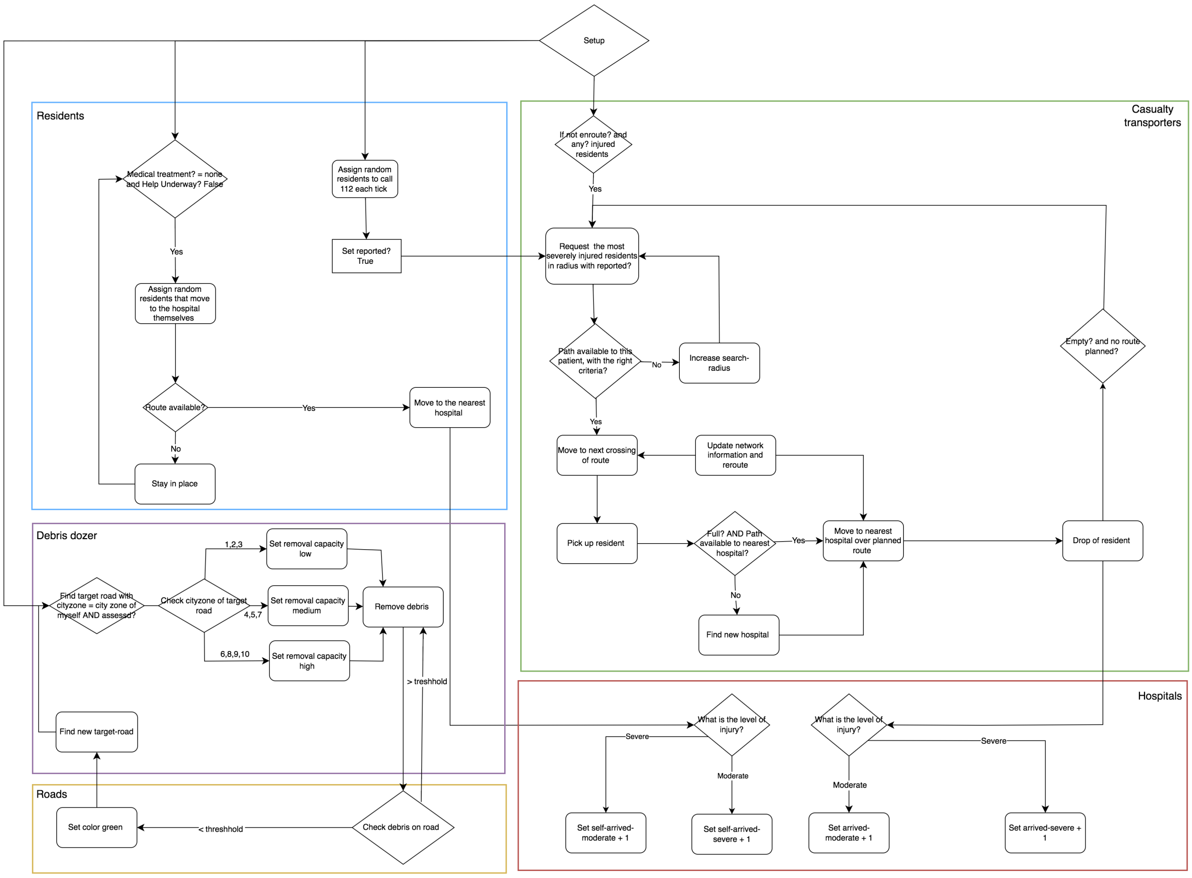


Figure 5.5: Full conceptual model

5.5. Key Performance Indicators (KPI)

Chapter 4 performed a literature review on how effectiveness is used in earthquake response models focusing on debris removal and the medical response. In the medical response effectiveness seems to focus on patient outcomes in the form of injuries and deaths. A low response time is also often considered as a metric for response effectively. For debris removal, the measures are usually related to network connectivity. However, as the aim of this research is not to optimize network recovery, but to explore the impact of different strategies in a more practical way, network connectivity is not considered a relevant measure. Therefore, whilst keeping in mind these focuses and considering the scope and narrative scenarios, the following indicators are found relevant to measure the effectiveness of the response and are thus the KPIs in the model.

- Number of injured residents receiving medical assistance
- Number of unreachable residents

The number of injured people receiving medical assistance is measured by four sub-indicators. The first two sub-indicators measure the number of severely and moderately injured individuals transported to hospitals by ambulance. The remaining two sub-indicators focus on those who arrive at the hospital independently, without ambulance assistance.

The number of injured residents who are inaccessible to emergency services. This is measured by the number of residents that cannot be reached from the hospital. This KPI is also tracked for each city zone within the model. While this measurement may not directly reflect the effectiveness of casualty transportation, it provides valuable insight into the effectiveness of the debris removal efforts and the overall accessibility of the affected areas. Additionally, it highlights the potential for improving emergency response capabilities and delivering timely assistance to those in need.

For the model, these KPIs have been conceptualized as shown in Table 5.5.

Table 5.5: Conceptualization of KPI's

KPI	Description
Assisted residents	Total number of residents located on the hospital node
Assisted severe	The number of severely injured residents located on the hospital node and are severely injured and dropped of by a casualty transporter
Assisted moderate	The number of moderately injured residents located on the hospital node and dropped of by a casualty transporter
Self severe	The number of severely injured residents located a the hospitals nodes **not** dropped by a casualty transporter
Self moderate	The number of moderately injured residents located a the hospitals nodes **not** dropped by a casualty transporter
Unreachable residents	Total number of residents without a path available to the hospitals

5.6. Debris removal strategies

Many studies have paid attention to clearing blocked roads and the management of debris and waste during the recovery phase. However, clearing debris to enhance rescue, save lives, and prevent more accidents is also a very important issue (Heydari et al., 2021). Many different approaches and strategies can be identified to manage debris removal in the response phase. A debris removal strategy in this thesis is conceptualized in the way the debris removal resources are distributed throughout the city, given a certain amount of resources available.

Like mentioned in section 5.4.1, the city is divided into different zones of which each has different characteristics. For this study the following characteristics are considered relevant: population density and the average distance to the hospitals. These characteristics can define the way the available resources are distributed throughout the city zones of the road network. This distribution is based on prioritizing city zones with certain characteristics and assigning more resources to the areas that score high on the criteria considered. These strategies and distribution are elaborated on in more detail in section 6.7.1.

5.7. Modeling assumptions

During the modeling phase, several assumptions are made for simplification reasons or when no data is available. Some of these assumptions were already presented throughout the description of the conceptualization. However, Table 5.6 provides an overview of the most important assumption used in the model for each aspect of the model. The full list of assumptions categorized by agent or object can be found in Appendix A.

Table 5.6: Main assumption

Model aspect	**Assumption**
Casualty transporters	Casualty transporters prioritize picking up the most severely injured resident who is reported
Residents	Residents are either located on the crossing, in a casualty transporter or inside a hospital
Hospitals	Hospitals in the model have unlimited capacity
Debris removal vehicles	Debris removal vehicles operate in one zone of the network
Roads	Roads are either accessible or blocked
Debris	One type of debris and equipment is modeled
Network	Traffic is not considered in the model

6
Formalisation and implementation

This chapter will give an overview of how the conceptualisation of the previous chapter develops into the actual Netlogo model by formalizing the conceptualization and thereafter implementing this into the Netlogo environment. This chapter begins by introducing the formalization of the network model, followed by an overview of the seismic scenarios considered and their characteristics. Next, the various aspects of the model are detailed and formalized. The chapter concludes with a description of the model's implementation, covering the creation of the graph, parameterization, and the behavior of casualty transport vehicles Lastly verification and validation is covered and the experimental design is introduced.

6.1. Network model

QuakeCity has a transportation and building network. Like mentioned in Chapter 2, the topography of the road network and the buildings are inspired by the city of Turin in Italy. This section will give an overview of the road and building network that create the earthquake environment. The total transportation network of *QuakeCity*, which is based on the topography of Turin is shown in Figure 6.1.

Figure 6.1: Road network (Marasco et al., 2021)

6.1.1. Buildings and hospitals

The building portfolio consists of four sections including housing, education, business, and public services. Within the scope, and following the aim of this research, two types of buildings are considered relevant: residential buildings which are part of the housing section and hospitals which belong to the public services. With this in mind, the total building network of *QuakeCity* includes 23,420 residential buildings (Marasco et al., 2021). These buildings can be distinguished by two main building types: masonry buildings (37%) and reinforced concrete buildings (63%). Together these buildings create an area that has a population of 908.129 and covers an area of 120 km^2.

6.1.2. City zones

Like conceptualized, the *QuakeCity* has been divided into 10 different zones based on the administrative zones, which is a known characteristic of each building. The division of zones is shown in figure 6.2.

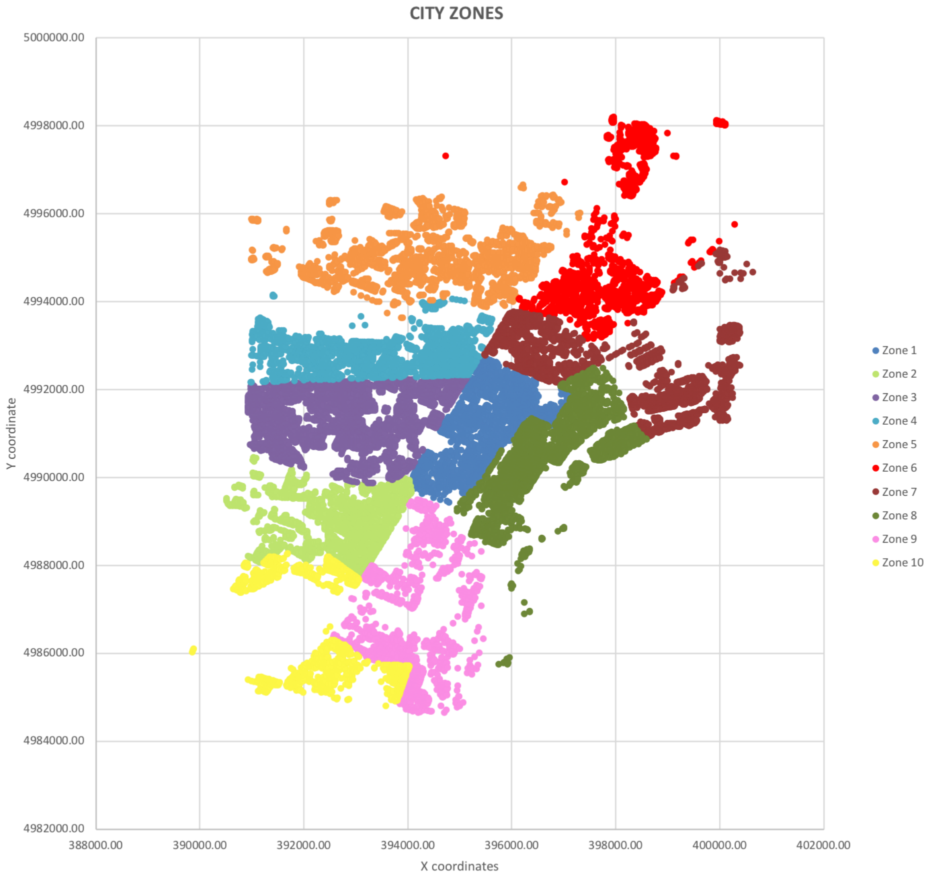


Figure 6.2: City zones

Each zone can be categorized by different characteristics. These specifications can later be used for implementing strategies in to the model. As conceptualized, this research first considers population density as a characteristic that can be used to base a strategy on. As areas with higher population density have more chance of more blockages due to more debris and more injured people if buildings collapse or get damaged. Another characteristic that can be valuable to base certain debris removal strategies on is the distance of certain areas to the hospitals in the city. Calculations and specific numbers can be found in Appendix B. Based on the population density the zones can be put into three different levels. Based on the distance to hospitals the zones can be put into three different levels. These characteristics can be used to base the distribution of the debris removal resources whilst testing the strategies in the final model, these distribution can be found in Appendix B. Table 6.1 shows the distinction between the zones based on the aforementioned characteristics.

Table 6.1: Population density and distance to hospitals in city zones

Population density	City Zones
High	1,2,3
Medium	4,5,7
Low	6,8,9,10

Distance to hospitals	City Zones
Low	1,3,8
Medium	2,4,7
High	5,6,9,10

6.2. Earthquake scenarios

The model under consideration operates within the road network presented in 6.1. As this model aims to evaluate various debris removal strategies, it is crucial to establish a setup that identifies which roads are blocked by debris and the locations of injured individuals throughout the network. This setup serves as the initial state for the model.

The setup in the model depends on what seismic scenario is considered. In this research, two benchmark scenarios are used, which result in the initial setup. According to Marasco et al. (2021) and Battegazzorre et al. (2021), el Centro can be considered to simulate a far-field seismic event, whilst the Kobe event is representative for simulating near-field earthquakes. The impacts of a far-field earthquake are generally less severe than near-field earthquakes. Table 6.2 presents the seismic characteristics of these earthquake events.

Table 6.2: Benchmark scenarios

Characteristic	El Centro	Kobe
Date	18/05/1940	17/01/1995
Location	Imperial Valley	Hyogoken Nanbu
Magnitude	6.9	6.8

These scenarios have been thoroughly calculated by Marasco et al. (2021) and Battegazzorre et al. (2021) for the road and building network presented in chapter 6.1. These result in the initial setups for for each scenario, which are presented in table 6.2. These numbers are conducted from different data files, of which some snapshots are provided in Appendix B.

Table 6.3: Setup model

Characteristic	El Centro	Kobe
Number of moderate injured people	9974	10044
Number of severely injured people	1658	1711
Number of blocked roads	2726	4005
Percentage of blocked roads	14.5	21.3

The main difference between the two scenarios is the fact that in the Kobe scenario, there is a significantly higher percentage of blocked roads and a slightly higher number of injured people. This means the initial damage of the Kobe scenario is higher compared to the initial damage of the El Centro scenario.

6.3. Formalisation of model aspects

All the existing data has been modified to be able to formalize for implementing the data is Netlogo. Some snapshots are presented in Appendix B to showcase the nature of these datasets. In addition, data is obtained from available literature and governmental reports. Lastly, some assumptions are made about the model input variables.

Injured residents

Like conceptualized, injured residents can have two different levels of injury: moderately injured or severely injured. Slightly injured residents and dead residents are not modeled. The location of the moderate and severely injured residents are based on a data set containing building characteristics. The injured residents located in all buildings closest to a crossing are created on that crossing, as crossings represent all buildings that are closest to that crossing. This means some crossings have many injured residents, whilst others have a few or even none. In order to prioritize severely injured residents to be picked up first, a health value between 0 and 100 is randomly assigned to all residents linked to the level of injury. These levels are shown in table 6.4.

Table 6.4: Health level of injured residents

Injury level	Health level
Moderate	50-100
Severe	0-50

Many injured residents move to the hospital by themselves. In order to achieve this, a number of injured residents are asked to move to the nearest hospital by themselves. To reduce complexity, self-movers do not follow the roads in the network, but simply move from the node to the hospital. However, to make sure only residents move if there is a path to the hospital consisting of accessible roads, this is first checked before the residents are moved to the hospital. If there is no path available towards the hospitals, the resident will stay in place.

Hospitals

The hospitals in *QuakeCity* treat the injured residents that arrive at the hospital. The common healthcare planning ratio suggestion of at least one hospital per 100,000 to 150,000 residents is supported by various urban planning guidelines and benchmarks observed internationally. This ratio helps ensure adequate healthcare coverage and accessibility in urban areas. Therefore, there are 8 hospitals within the network in the model to suit the population present in *QuakeCity*. The location of the hospitals in the model are based on the real location they have within the road network. As the scope does not include treatment within the hospitals, the hospitals are assumed to provide the right care to all injured residents that arrive and thereby do not have capacity limitations.

Ambulances

The average number of ambulances per hospital in different countries varies significantly. This number is influenced by factors such as population density, healthcare infrastructure, and emergency medical services demand. However, international standards recommend the provision of 1 ambulance for every 50,000 people to fulfil the demand for transporting patients to definitive care facilities (Debas et al., 2015). However, during emergency situations, it is very common that partnerships are in place which can increase the capacity of available ambulances. So considering this information, 25 ambulances operate within the base model.

In the model the ambulances have an initial search radius in which they operate. If they cannot find a target patient in that radius, they increase their search radius. This is modeled, to include efficiency within the response. For example, it is more efficient to first pick up a patient nearby, instead of going to the opposite part of the city. Ambulances typically are equipped to transport one severely injured patient at a time (Ambulance Zorg, 2024). This is because the space and medical equipment in an ambulance are designed to provide the necessary care and monitoring for one critical patient. This is also incorporated in the model, ambulances can only pick up one resident at the time.

Roads and Debris

Under the described seismic scenario, it is already known which roads are blocked and cannot be used for casualty transportation. In real life, it is not known which roads are blocked and which roads are not. Therefore, damage assessment is necessary to investigate the earthquake-struck area and to map out blocked roads in which helicopters and drones play a viral role (Graphics, 2024). In the model damage assessment is modeled as roads reporting themselves as blocked over time. Initial road assessment can usually be done within a few hours, with comprehensive assessments taking a bit longer. However, with current advanced technologies, comprehensive assessments can be completed within 1 to 3 days for a medium-sized urban area. This means that after 3 days the whole network is assessed, and it is known which roads are blocked and which roads are not blocked. This is incorporated into the debris removal model, as the debris removal vehicles only clear roads that have been assessed.

It is not known exactly how much debris is generated on each individual road. Therefore, debris is randomly generated over roads that are known to be blocked. The volume, however, like conceptualized, is assumed to be related to the length of the road. The lengths of the roads in the graph differ a lot and vary from 0,004 to 2200 meters. Therefore, 4 levels of debris volumes are defined. All roads then generate debris within the range that is connected to the category the road is in. In practice, this means it takes longer to clear longer roads than it takes to clear shorter roads or connections in the model. The categories are shown in table 6.5 and are based on calculations by FEMA (2007). Each of the categories has its own threshold. This threshold showcases the volume that is needed for the road to be accessible for ambulances.

Table 6.5: Debris volume

Category	Road length (m)	Debris volume	Threshold
Small roads	< 10	10-50m^3	10m^3
Medium roads	> 10 x < 100	50-300m^3	50m^3
Large roads	> 100 x < 1000	300-1000m^3	200m ^{3}
Very large roads	> 1000	1000-5000m^3	900m^3

Debris dozers

Like mentioned in chapter 3, various equipment is used for debris removal depending on the category and size of the debris. For the model, it is assumed that one type of bulldozer is used to push debris to the side of the roads. These debris removal vehicles have a certain capacity to move debris to the side of the roads. This is based on the capacity and efficiency data of bulldozers and is set to the capacity of moving 120 cubic meters per hour. This is based on an average between medium-sized bulldozers and large bulldozers (Caterpillar, 2023). However, as conceptualized, highly populated areas might be harder to reach and manoeuvring on the narrower roads is hard. Therefore, the capacity of each dozer is adjusted to he characteristics of the zone that it is operating in. The capacity ranges from 85, in more densely populated areas to 120 cubic meters in the neighborhoods that are less densely populated.

Army vehicles

The army vehicles use the same logic to move around the model as ambulances. However, given that army vehicles are typically designed to be more robust and capable of navigating over rough terrain and debris, the thresholds for road accessibility for these vehicles can be set at higher levels than for ambulances. As these vehicles are more robust, they are able to drive over roads that are not yet accessible for ambulances. They can thus, reach injured residents that are not yet reachable for regular casualty transportation by ambulances. This means the threshold to be able to be used in routing is higher. These thresholds are shown in table 6.6.

Table 6.6: Army vehicles thresholds

Category	Threshold
Small roads	40m^3
Medium roads	150m^3
Large roads	500m^3
Very large roads	1500m^3

6.4. Model implementation

The previous sections have shown how the conceptual model is formalized. In the next steps, the implementation of the model, the conceptual system is put into the model environment. The agent-based model is built in Netlogo, which enables agent-based models to be implemented with a relatively easy syntax. However, it is challenging to create more complex models and required many assumptions. Some of these assumptions have already been mentioned in chapter 5. A list of all model assumptions can be found in Appendix A.

This section will start by showcasing the map and visualization, followed by the parametrization, the model interface and the pseudo-code.

6.4.1. Map and visualization

Like conceptualized, the road network is modeled as an un-directed graph containing of 14,239 nodes and 18,789 links. The nodes and links represent crossings and roads. Figure 6.3a shows the road network with the buildings plotted in the map in Netlogo. However, as the buildings are not a part of the network itself, they have been connected to the closings crossing. This means that all crossings represent all the buildings that are closest to that crossing, including all injured residents from those buildings. Figure 6.3b presents the network used in the simulation, including the injured residents, hospitals and ambulances. The network is first created through a series of steps and then saved as a GraphML file. This approach allows for the network to be initialized in one step during experimentation, eliminating the need to regenerate or plot the entire network from raw data with each simulation run. Using a GraphML file streamlines the setup process and improves efficiency.

(a) Road and building network

(b) Road network

Figure 6.3: Visualisation of road network

Hospitals are represented as white houses. Ambulances are portrayed as white cars and injured residents are presented as persons located on the crossings. The Army vehicles are represented by trucks and debris removal vehicles are portrayed as a bulldozer. Roads can have three different colors. Available roads are blue, red roads are blocked from the beginning of the simulation depending on the seismic scenario under consideration. Red roads can become green once they have been made accessible by one of the debris removal vehicles. A zoomed-in shot is which showcases this is presented in 6.4.

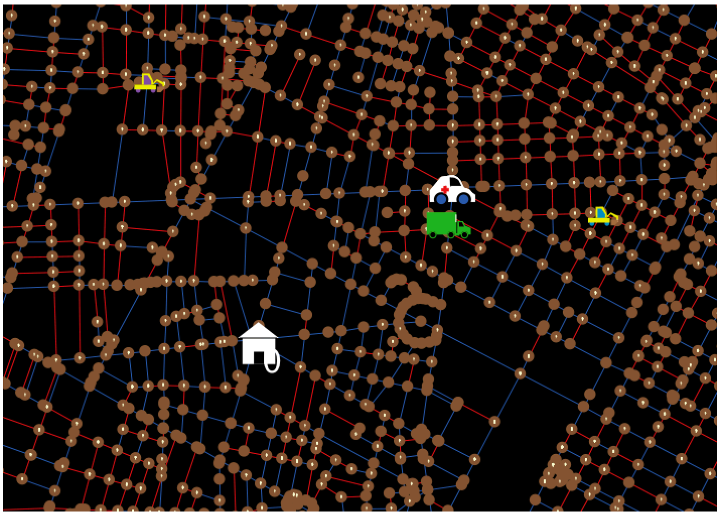


Figure 6.4: Zoomed in picture of the model

6.4.2. Time sequence

The model runs in discrete time steps in which each time step represents 1 minute. The decision is based on the fact that routing of the casualty transportation vehicles is a crucial part of this model. Incorporating this is a good matter that requires small time steps. Additionally, as the model focuses on earthquake response, which is usually considered to be 1-3 days, small time steps are more appropriate.

When agents are being activated, agents execute their agent step sequentially and not simultaneously. This means the agent will carry out the procedures programmed in the agent-step one after another in the order that they are presented in the code. This order has been carefully chosen, as the order can have an impact on the behavior of the model. For example, the reporting of roads will always happen before the debris dozers are activated and the hospitals are always updated in the last step of the go procedures.

Some actions within the model are not executed at every time step, but rather every 60 time steps, representing an hourly occurrence. This adjustment is made because the model is relatively complex, and the time steps are intentionally small to ensure accurate vehicle routing. The decision to space out these actions every hour helps to ensure the smooth operation of the model.

A complete run contains 4320 steps, which is 3 days in total. This run time will give a good indication on how the model performs in comparison to the real-world observation.

6.4.3. Parametrization

The parametrization step determines the model values for the parameters in the conceptual model. The model variables are divided into four categories. A complete overview of all parameters and model values can be found in Appendix C.

Table 6.7: Categories and their Descriptions

Category	Description
Model	The global values of the initial settings of the model
Agent properties	The characteristics of agents
Simplifying the model	Variables and decision which make the model easier to interpret
Settings for interventions	The strategy variables for implementing the different resource distributions

6.4.4. Behavior of casualty transporters

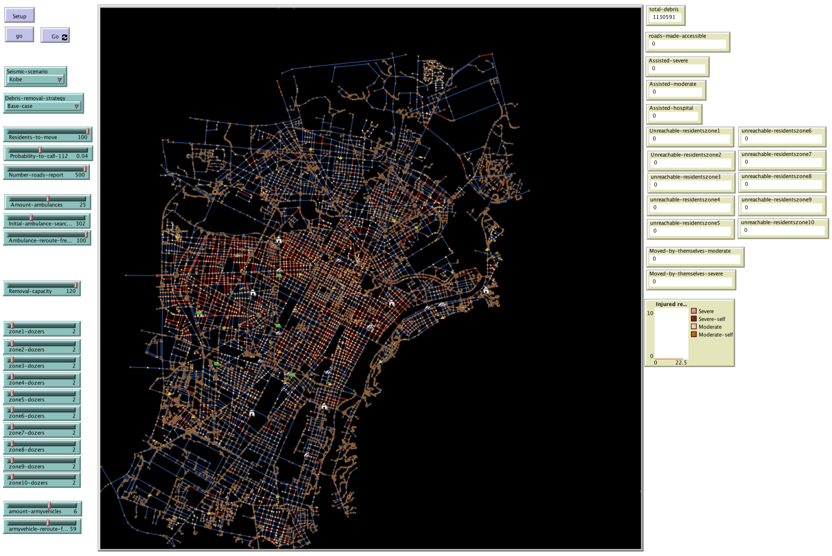
One of the main ways in which the logic from the conceptual models could be translated and implemented in the agent-based model is by the use of the NW extension in Netlogo. The NW extension helps simulate and analyze the movement and interaction of agents across networks by providing various path finding and network analysis capabilities (NetLogo, 2024).

The behavior of the casualty transporters in the model are implemented utilizing the NW extension in Netlogo. Using this extension allows to model the navigation in the network with blocked and unblocked roads, which is the goal of modeling the casualty transporters. Like conceptualized, the casualty transporters follow the following steps: request a patient, plan a route, move over the network, pick up a patient, plan a route to the hospital, drop off at the hospital. Using the NW extension, the code generates the shortest path for ambulances from their location to the target-patient, considering only accessible roads (marked blue or green), while avoiding blocked roads (marked red). If there is no path available, a new patient is targeted. For the army vehicles, the same logic is applied, however the code generates the shortest path from their location to the target patient, considering only roads of which the available-for-army variable is set to true. This is based on the debris volume on the roads and are all the blue and green roads and some red roads. Over time, as debris removal progresses, more red roads become accessible to army vehicles, with the available-for-army variable being updated accordingly. In the move procedure, the casualty transporters moves to the next node of the sequence that is generated by the model. When arriving at the node of the resident, the same logic for the way back to the hospital is used. Once the patient is dropped of, the process starts again. As debris removal occurs at the same time as casualty transportation, some roads become available over time. Therefore, the casualty transporters update the network information every 60 ticks, which allows the casualty transporters to change routes during a trip to a patient if a shorter route becomes available.

This approach ensures that ambulances navigate efficiently through the urban network by avoiding blocked roads and recalculating paths when necessary, ensuring an effective response despite debris-related obstacles.

6.4.5. User interface

The interface of the model is shown in figure 6.5. In the middle, the output of the model is visually displayed. On the left side of the interface, some input parameters can be set and varied if necessary. On the right side, the output of certain parameters are shown in numbers or graphs and the KPI's of the model are displayed.



Seismic-scenario Kobe
Debris-removal-strategy Base-case
Residents-to-move 100
Probability-to-call-112 0.04
Number-roads-report 500
Amount-ambulances 25
Initial-ambulance-searc... 302
Ambulance-reroute-fre... 100
Removal-capacity 120
zone1-dozers 2
zone2-dozers 2
zone3-dozers 2
zone4-dozers 2
zone5-dozers 2
zone6-dozers 2
zone7-dozers 2
zone8-dozers 2
zone9-dozers 2
zone10-dozers 2
amount-armyvehicles 6
armyvehicle-reroute-f... 59

total-debris 1130591
roads-made-accessible 0
Assisted-severe 0
Assisted-moderate 0
Assisted-hospital 0
Unreachable-residentszone1 0
unreachable-residentszone6 0
Unreachable-residentszone2 0
unreachable-residentszone7 0
unreachable-residentszone3 0
unreachable-residentszone8 0
unreachable-residentszone4 0
unreachable-residentszone9 0
unreachable-residentszone5 0
unreachable-residentszone10 0
Moved-by-themselves-moderate 0
Moved-by-themselves-severe 0

Figure 6.5: User interface of the Agent-Based Model

6.4.6. Pseudocode

A pseudocode is presented in Appendix D, where it is possible to see a top-level view of the logic behind the code.

6.5. Verification

An important step in modeling is verifying that the formalized concept behaves as intended. Verification aims so answer the question *Have we built the thing right?* . Verification increases the confidence in the model and the outcomes. Additionally, verification ensures that no unintended model behaviour changes the results of the model.

Verification has been done continuously during the designing and building of the model to assure the worked as was intended. The building phase of the model has been an iterative process in which new elements were only added after the current model worked as was intended, to prevent chaos during the modeling. Multiple verification test are performed. The following tests were used for the verification of the model.

- Extensive code walk-through
- Recording and tracking Agent behaviour

First the model code was checked during various stages of model development. This means checking if the model functions were correctly translated from the conceptual model and procedures. To verify the model operation relevant output variables are selected and monitored by recording and tracking agent behaviour. A detailed description of these verification steps is shown in Appendix E.

6.6. Validation

Model validation makes sure that the behavior of the model accurately reflects the behavior of the real-life system (Cooley & Solano, 2011). The validation of a model is a crucial step when there is a desire to use the model's results in a broader context. The goal of model validations is to determine whether the model represents the thing that it models (Van Dam et al., 2013). It needs to be checked if the model actually models an earthquake response accurately enough to interpret the result in a correct manner.

Performing a sensitivity analysis on the model parameters can increase validity. This analysis helps in understanding how changes in input parameters affect the results therefore, a sensitivity analysis has been performed on several model input variables. The detailed results of this analysis can be found in Appendix E. Most variables do not influence the KPI's in the base model significantly. However, variability occurs in the outcomes due to the way the model works, but the overall outcomes remains consistent. As expected the model is most sensitive to the number of ambulances that operate within the model. However, the variability in the outcomes decreases when in line with increasing the number of ambulances.

Earthquake response and events are very scenario-specific and the model outcomes are very dependent on the initial setup of the model. Therefore, the validation process focused on validating patterns and trends rather than exact numbers. For example, a general trend that comes from reports on earthquake reponses in urban areas is that a large proportion of injured people arrive at hospitals on their own, as ambulance care is reserved for severely injured residents. Furthermore, in urban areas, as good roads are usually in place, more people go to the hospitals by themselves. For example, during the Kobe earthquake, it was reported that around 40% of the injured reached the hospitals without ambulance services (Tanaka, 1996). In addition during the Christchurch earthquake, it was reported that a large number of injured people arrived to the hospitals by themselves (Ardagh et al., 2012). During the Northridge earthquake response the majority of injured victims arrived by private transportation (Stratton et al., 1996). During this earthquake response mainly seriously injured victims moved to the hospitals by available emergency services. These identified trends are also present in the model results, where a large part of the total assisted residents is represented by residents moving to the hospitals by themselves, especially the more moderately injured. Additionally, significantly more severely injured residents are moved by ambulances compared to moderately injured residents in the outcomes of the model. Table 6.8 shows summarized these trends and some examples from outcomes of the base case behavior.

Table 6.8: Summary of model validation

Identified response trend	Model outcomes assisted by ambulances	Model outcomes self transportation
Majority of injured victems arrived by private transportation (Stratton et al., 1996) (Ardagh et al., 2012) (Tanaka, 1996)	7% of total injured residents in the severe scenario and 10% in the less severe scenario	30% of injured residents in the severe earthquake scenario and 40% in the less severe scenario
Mainly seriously injured residents are moved by ambulance services (Stratton et al., 1996)	94% of assisted by the ambulances are severely injured residents in the severe earthquake scenario and 97% in the less severe scenario	

Regarding debris removal, it is very challenging to validate the outcomes with other literature. Mainly because there is no data about the amount of debris removed or number of cleared roads in the emergency response following an earthquake event, as most literature focuses on the recovery phase regarding debris removal or does not use realistic debris generation as most studies regarding debris removal focus on optimizing the sequence of roads to clear, rather than the impact it has on the emergency response. However, the initial amount of generated debris from the model can be compared to other earthquake events. Although, very event-specific, this number has the same order of magnitude compared to the earthquakes mentioned in chapter 3. Additionally, the amount of debris is significantly lower in the less severe earthquake scenario, which aligns with real-world observations following seismic events. To illustrate this, Table 6.9 presents the debris volume generated in the model for both seismic scenarios. It is important to note that the model only generates debris on roads that are blocked, and the simulation focuses solely on the city centre rather than the entire affected area. As a result, the debris volume does not account for debris generated on unblocked roads or outside the modeled geographical area, which may underestimate the total debris compared to real-world scenarios.

Table 6.9: Validation of generated debris

Seismic scenario	Initial debris in model
Kobe	1,100,000 m^3
El Centro	750,000 m^3

6.7. Experimental design

This section will introduce the two prioritization strategies for distributing the debris removal resources throughout the virtual city that will be tested in this thesis. Additionally, a contingency strategy is introduced. Furthermore, the experimental design and the variables changes are introduced.

6.7.1. Debris removal strategies

A debris removal strategy in this thesis contains the number of resources available, which are the ambulances and debris dozers in the model and the way these debris removal resources are distributed throughout the city zones. As the success of debris removal depends on both the quantity of equipment deployed and the strategic allocation of those assets to different zones. Even with a large number of resources, if they are concentrated in less critical areas or distributed inefficiently, the overall response may be delayed. Conversely, with fewer resources, optimal distribution becomes crucial to prioritize zones with the greatest need, such as those with high population density or proximity to hospitals. Strategy requires a careful balance between resource availability and strategic allocation. Furthermore, a less traditional strategy is tested, which is using army vehicles to improve the initial response. Table

6.10 gives an overview of the strategies tested in this thesis.

Table 6.10: Debris removal strategies

Strategy name	Strategy type
Population density	Resource distribution strategy
Distance to hospitals	Reource distribution strategy
Deploying army vehicles	Supplementary strategy

There are many ways to prioritize areas. One potential strategy for debris removal is to prioritize high-population density areas. In highly densely populated areas, there are typically more buildings, and consequently, more structural damage occurs during disasters. This leads to a larger volume of debris that could obstruct roads, hamper emergency response efforts, and block access to vital services. Moreover, the concentration of people in these zones increases the probability of a higher number of victims who may be injured. By focusing debris removal efforts in these high-density areas, emergency responders can quickly restore access to key routes, enabling faster medical interventions and rescue operations. The removal of debris in such areas allows ambulances and rescue teams to move more efficiently. This strategy is referred to as **population density**.

Another strategy is to prioritize areas close to hospitals, as this will create accessibility of the hospitals during an emergency, which is crucial in assisting injured people. Ensuring clear access to hospitals is crucial in disasters. Hospitals are key to treating injured victims, and removing debris near these facilities ensures that patients can reach critical care without delays. This strategy prioritizes accessibility, which could save lives by reducing the time it takes to transport injured individuals to hospitals. This strategy is referred to as **Distance to hospitals.**

Debris removal strategies may struggle to cope with the vast scale of destruction, especially in dense urban environments. In these cases, relying solely on debris removal to clear routes for emergency vehicles can lead to significant delays, which are critical when transporting injured residents to medical facilities. To address this, military vehicles can serve as a contingency strategy, supplementing traditional transportation methods. These vehicles, with their robust off-road capabilities, can bypass blocked roads and operate in areas where debris removal has not yet occurred. While military vehicles don't engage in the direct removal of debris, their ability to navigate difficult terrain allows for quicker access to casualties, ensuring that injured individuals can be reached and transported more rapidly, even when ambulances are unable to operate due to road blockages. The introduction of military vehicles for casualty transport provides an alternative means of ensuring that medical evacuations continue uninterrupted, reducing the reliance on fully cleared roads and enhancing the overall resilience of the emergency response system.

6.7.2. Experimental set-up

First the setup of the base case is clarified. In this research, there are two base case experiments, as there are two different initial damage setup possibilities. In the base case, the debris removal resources are distributed evenly throughout the model network. This results in the following two experiments portraying the base case shown in table 6.11.

Table 6.11: Base case variables

ID	Seismic scenario	Removal strategy	Number of ambulances	Number of dozers
BC1	Kobe	Evenly distributed	25	20
BC2	El Centro	Evenly distributed	25	20

The experimental design consists of experiments that can be used to evaluate the influence of the different strategies. The variables that are varied and their levels are presented in Table 6.12.

Table 6.12: Variables and their ranges for the simulation experiments

Seismic scenario	Removal strategy	Number of ambulances	Number of dozers
Kobe	Based on Population density	25	20
El Centro	Based on Distance to hospitals	35	40

The ambulance availability ranges between 25 and 35 units. The lower bound of 25 ambulances is based on the data provided in section 6.3. The decision to explore increasing this number to 35 ambulances stems from the desire to evaluate the impact of additional resources in the system. Resource availability of 35 is chosen to balance practicality with reality. This moderate increase allows for an insightful analysis without exceeding what would be operationally feasible.

The dozer availability ranges from 20 to 40 dozers. This decision was driven by a sensitivity analysis, to see when adding more dozers would have some effect. By doubling the number of dozers, the model allows for a thorough evaluation of how increased resources influence the effectiveness of debris removal strategies, providing insights into the optimal allocation of equipment without exceeding operational limits.

The removal strategy reflects the way the debris dozers are distributed throughout the zones in the city. These distributions are based on the different characteristics introduced in section 6.1.2. The specific distributions are shown in Appendix B. The resources are reflected by the number of debris removal dozers and the number of ambulances operating in the model. All experiments will be evaluated based on the key performance indicators.

This experimental setup results in 16 experiments. This results in the following experimental design, shown in 6.13.

Table 6.13: Experimental design

ID	Earthquake	Number of ambulances	Number of dozers	Debris Removal Prioritization
1	Kobe	25	20	Population density
2	Centro	25	20	Population density
3	Kobe	25	20	Distance to Hospitals
4	Centro	25	20	Distance to Hospitals
5	Kobe	25	40	Population density
6	Centro	25	40	Population density
7	Kobe	25	40	Distance to Hospitals
8	Centro	25	40	Distance to Hospitals
9	Kobe	35	20	Population density
10	Centro	35	20	Population density
11	Kobe	35	20	Distance to Hospitals
12	Centro	35	20	Distance to Hospitals
13	Kobe	35	40	Population density
14	Centro	35	40	Population density
15	Kobe	35	40	Distance to Hospitals
16	Centro	35	40	Distance to Hospitals

To evaluate the impact of military vehicles on the overall effectiveness of the emergency response, a series of experiments were added to this experimental design. The ”Kobe” scenario is used as the test environment for assessing the influence of military vehicles. This results in 8 extra experiments shown in table 6.14. This finalizes the experimental design which consists out of 24 experiments.

Table 6.14: Experimental design army vehicles

ID	Earthquake	Number of ambulances	Number of dozers	Debris Removal Prioritization	Military vehicles
17	Kobe	25	20	Population density	5
18	Kobe	25	20	Population density	10
19	Kobe	25	20	Distance to hospitals	5
20	Kobe	25	20	Distance to hospitals	10
21	Kobe	35	20	Population density	5
22	Kobe	35	20	Population density	10
23	Kobe	35	20	Distance to hospitals	5
24	Kobe	35	20	Distance to hospitals	10

7

Model results

This chapter presents the results derived from the experimental design presented in the previous chapter. Using two seismic scenarios, Kobe and El Centro, the chapter first analyzes the base case behavior of the two base case experiments, followed by the results of all experiments. This chapter is finalized by validating the model. This chapter aims to further answer sub-question 4:

What are some potential debris removal strategies and to what extend can these strategies enhance the effectiveness of an earthquake emergency response in urban areas

The model of *QuakeCity* is considered under the two earthquake scenarios introduced in chapter 5. Like mentioned, the biggest difference between these scenarios in the setup of the model in the initial damage showcased by the number of blocked roads. Using these two scenarios allows for insight in the different impact of certain strategies in events with more damage and blocked roads and in events with fewer blocked roads.

In this chapter multiple terms are used in discussing the results. An experiment refers to one of the experiments presented in the experimental design. A scenario presents the initial damage state that is present in the experiment. A zone reflects a specific geographical area of the total network and the removal strategy reflects the way the debris removal resources are distributed throughout these zones in the city.

The results of the experiments are divided into four categories. First, the base case experiments are discussed. Next, the experiments using the Kobe scenario are presented, followed by those conducted with the El Centro scenario. Finally, the results of the experiments involving the deployment of army vehicles are presented.

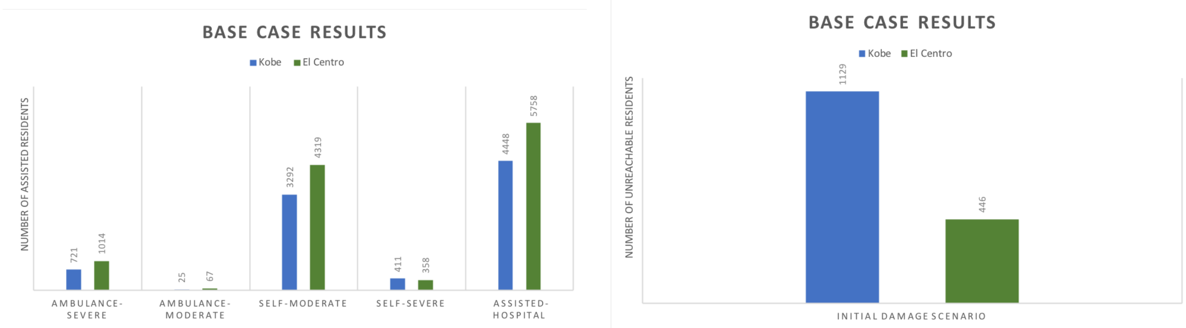
7.1. Number of runs and randomness

In the model described, several procedures depend on probabilistic distributions and random variables. For example, the roads that are targeted for debris removal, the distribution of ambulances over the hospitals and the sequence in which injured residents report themselves. As a result, running the model only once would not provide reliable results, as the outcome could be influenced by extreme values or random variation. To obtain more robust insights, it is essential to perform multiple runs of the model. However, due to computational constraints, it is not feasible to execute the model an unlimited number of times.

To balance accuracy with practicality, each experiment was initially run five times, allowing for the generation of an initial set of results. This repetition helps to account for variability and reduces the likelihood that any observed effects are purely due to chance. In some cases, however, the initial five runs did not reveal statistically significant differences in the variables or patterns under investigation. To address the potential limitations of sample size, an additional ten runs were conducted per experiment, bringing the total number of executions to 15. While this extended approach enhances the robustness of the results and improves confidence in the conclusions drawn, it is important to recognize that some variability may remain, and not all findings may be statistically significant. These aspects will be discussed further in the presentation of the results below and elaborated on in section 8.1. The full explanation and results of the significance testing can be found in Appendix G.

7.2. Base case behavior

In this first section the behavior of the base model is presented. Figure 7.1a shows the average number of residents that are assisted and Figure 7.1b shows the average number of unreachable residents at the end of the simulation. Both KPI's are shown for the two seismic scenarios that are used in this thesis. These scenario's have a different initial impact when the model is setup. The blue indicates the ”Kobe” scenario whilst the green portrays the ”El Centro” scenario. These colors will be used to portray these scenarios throughout all results presented in this chapter.



(a) Assisted residents **(b)** Unreachable residents

Figure 7.1: Indicators base case

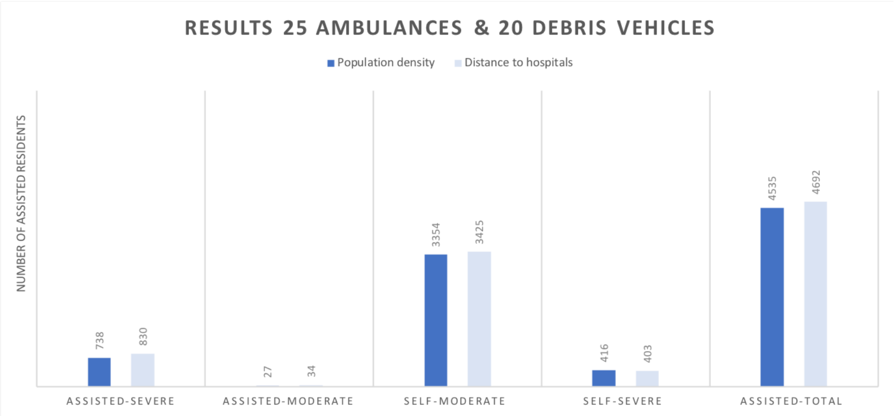
The two base case experiments clearly demonstrate the impact of initial damage after the earthquake on both key performance indicators. In the ”El Centro” scenario, where fewer roads are blocked at the start of the simulation, approximately 6,000 residents are assisted. In contrast, the ”Kobe” scenario allows for the assistance of around 4,500 residents. This indicates that the level of initial damage significantly affects how many people can be assisted with the same resources. El Centro manages to assist more people despite utilizing similar resources as Kobe.

The majority of the assisted residents consist of those who independently travelled to the hospital. Additionally, a significant portion of the total comes from severely injured residents who were assisted by ambulances. Although there are many more moderately injured residents compared to severely injured ones, the model shows that more severely injured residents receive ambulance assistance. This is due to the model's prioritization of severely injured residents over those with moderate injuries. Figure 7.1b compares the number of unreachable residents between the Kobe and El Centro scenario. Kobe has a significantly higher number of unreachable residents, close to 1,200, compared to El Centro, which has fewer than 450. This big difference suggests that in the Kobe scenario less people have been assisted, which might be caused by no routes being available to the residents or longer routes due to the high number of blocked roads. In contrast, in the El Centro scenario less challenges in this regard were present, which can correlate with the higher number of people assisted.

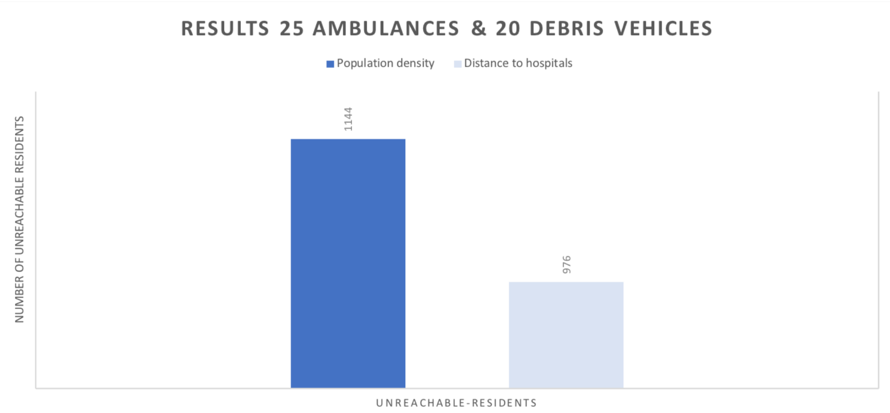
7.3. Results for the Kobe scenario

This section presents the results of experiments using the Kobe scenario as the initial setup in the model. The outcomes are compared by examining the different debris removal strategies under different resource availability's, highlighting the variations between these approaches across varying conditions. The figures represent the average values of each KPI across all experiment runs, providing a clear comparison of the performance between the two strategies. It must be noted that for the indicators of the assisted residents, an increase is considered a positive effect, whilst for the indicator of unreachable residents a decrease is considered to be a positive effect.

Figure 7.2 shows the results for experiments 1 and 3, in which the model has 25 ambulances and 20 debris dozers operating in *Quakecity*.



(a) Assisted residents 25 ambulances 20 dozers



(b) Unreachable residents 25 ambulances 20 dozers

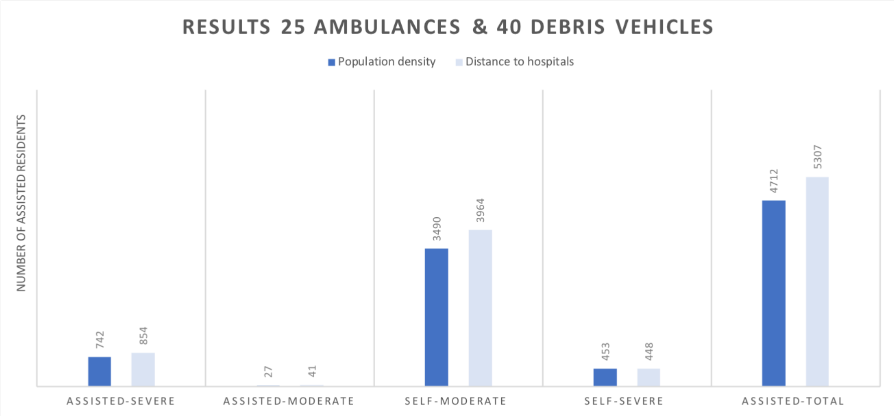
Figure 7.2: Results experiments 1 and 3

Both the population density and distance to hospitals strategy showed significant differences in the number of severely injured residents who were assisted. Distance to hospitals appears to have a stronger influence, as seen by the higher number of assisted residents compared to the population density strategy. This may be attributed to the fact that more residents are located in areas where the debris removal efforts are concentrated, suggesting it is a more efficient method of resource allocation when casualty transportation and debris removal capacities are limited. The results for moderately injured self-assisted residents were also significant, with a higher impact observed under the distance to hospital strategy, emphasizing the importance of proximity in moderate cases.

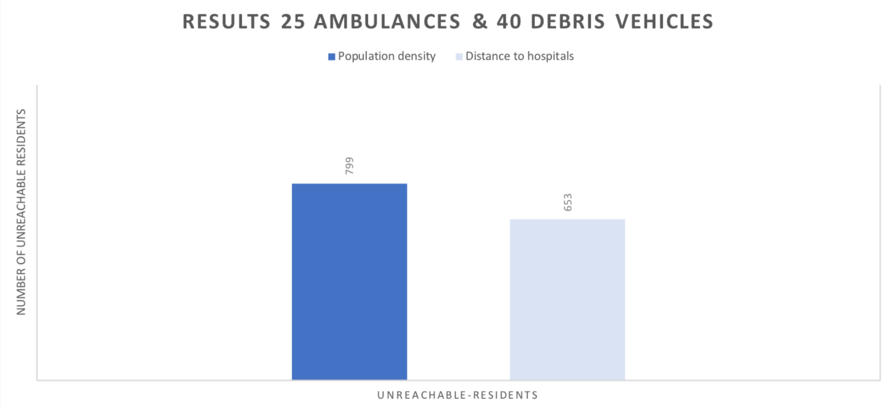
In the case of moderately injured residents requiring assistance, neither population density nor distance to hospitals showed a statistically significant effect. This suggests that other factors may influence the outcome for this group, or that the effect sizes in these areas were too small to detect in this experiment.

Similarly, the results for severely injured self-assisted residents did not show significant differences based on population density or hospital proximity compared to the base experiment for the Kobe scenario.

Figure 7.3 shows the results for experiments 5 and 7, in which the model has 25 ambulances and 40 debris dozers operating in *Quakecity*.



(a) Assisted residents 25 ambulances 40 dozers



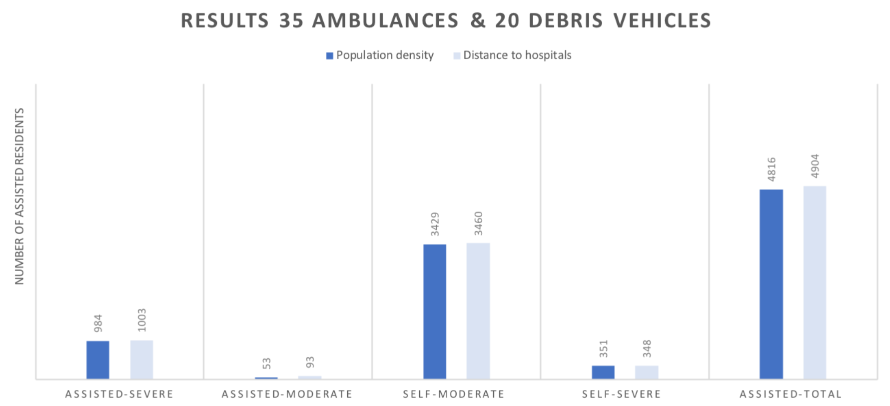
(b) Unreachable residents 25 ambulances 40 dozers

Figure 7.3: Results experiments 5 and 7

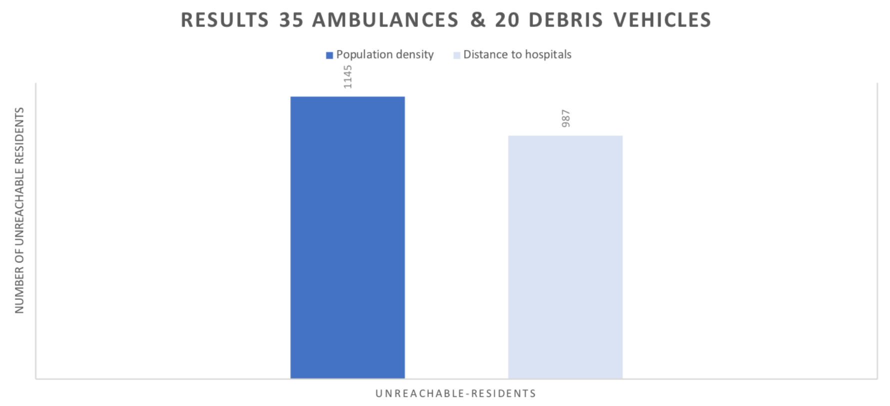
The results show that when more debris removal resources are available, the distance to hospitals strategy has a significant impact on moderately injured residents who self-assist. This increase can be explained by the enhanced accessibility of roads, as more debris removal resources open up routes to hospitals, thereby allowing more residents to seek medical assistance independently. As seen in the chart, a greater number of residents were able to self-assist under this strategy compared to the population density strategy. In addition, both strategies seem to have a significant impact on the number of unreachable residents, compared to the experiment with fewer resources available, highlighting the importance of debris removal for network accessibility.

However, for both strategies, the number of residents assisted by ambulances is not statistically significant. Meaning that the increase of debris dozers, whilst ambulance capacity is limited does not show significant improvement in the number of people that can be assisted by ambulances. This indicated that ambulances in this case are the main bottleneck.

Figure 7.4 shows the results for experiments 9 and 11, in which the model has 35 ambulances and 20 debris dozers operating in *Quakecity*.



(a) Assisted residents 35 ambulances 20 dozers



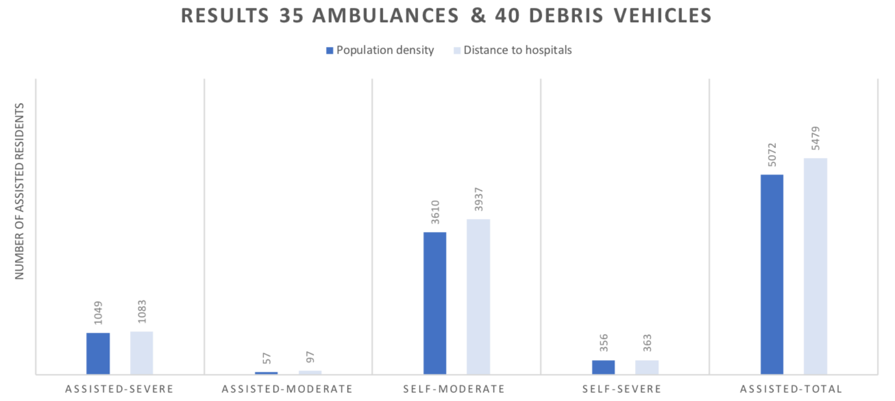
(b) Unreachable residents 35 ambulances 20 dozers

Figure 7.4: Results experiments 9 and 11

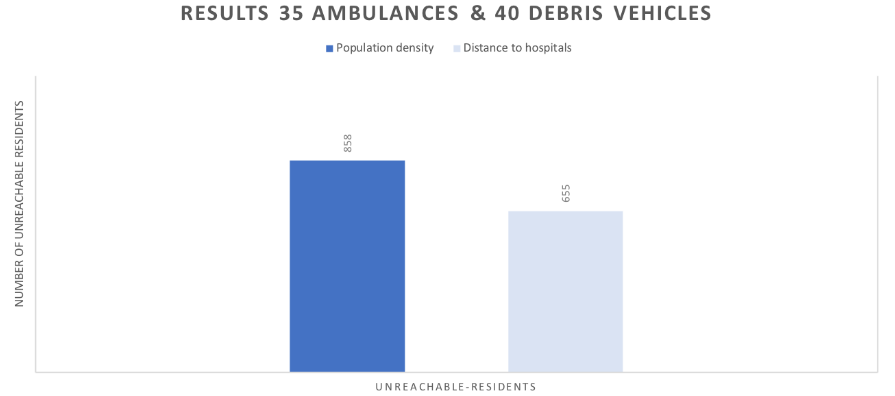
When additional ambulance capacity is introduced, while keeping the debris removal capacity limited there is a high increase in the number of people, both severely and moderately injured, that are assisted by ambulances, compared to the experiments with fewer ambulances. The distance to hospital debris removal strategy shows an ever bigger increase compared to the population density strategy. In addition, the distance to hospital strategy also shows significant increases in the number of residents that self-assist, whilst the population density strategy does not have statistically significant results for this KPI compared to the experiment with fewer ambulance availability.

Increasing the number of ambulances does not influence the number of unreachable residents at the end of the simulation compared to experiments with fewer ambulances. This is understandable because the ambulances themselves do not impact the overall transportation network, and thus also not the number of residents that cannot be reached due to debris.

Figure 7.5 shows the results for experiments 13 and 15, in which the model has 35 ambulances and 40 debris dozers operating in *Quakecity* under the Kobe scenario.



(a) Assisted residents 35 ambulances 40 dozers



(b) Unreachable residents 35 ambulances 40 dozers

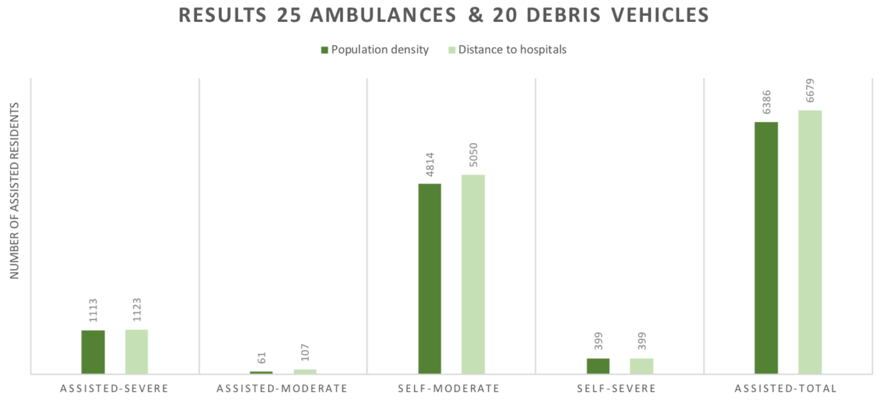
Figure 7.5: Results experiments 13 and 15

Both debris removal strategies demonstrate a similar impact on the number of severely injured individuals transported by ambulances, indicating that when resources are plenty, the specific debris removal strategy is less critical. However, a significant increase in self-assisted cases is observed, with the distance-to-hospitals strategy resulting in a greater increase compared to the population density-based strategy. The number of moderately injured individuals remains largely unaffected by either strategy, likely due to the model's prioritization of severely injured victims.

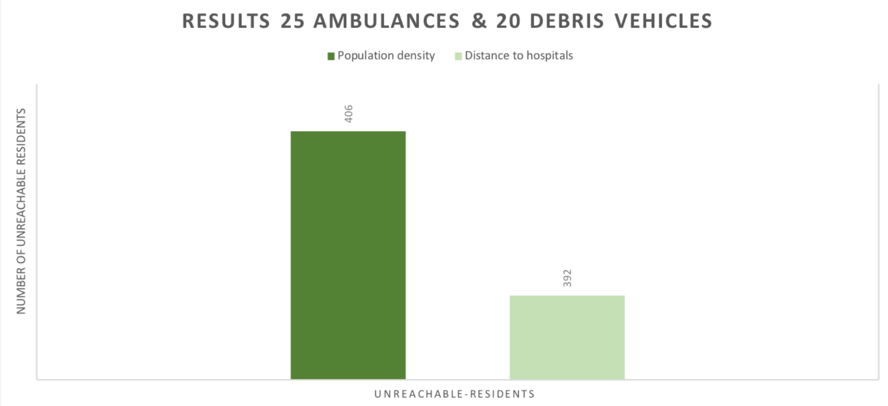
Furthermore, the distance to hospitals plays an even more critical role in decreasing the number of unreachable residents in the model. By using this strategy, an additional 200 residents become reachable for assistance compared to the population density strategy.

7.4. Results for the El Centro scenario

Figure 7.6 shows the results for experiments 2 and 4, in which under the El Centro scenario, 25 ambulances and 20 dozers are operating within *Quakecity*.



(a) Assisted residents 25 ambulances 20 dozers



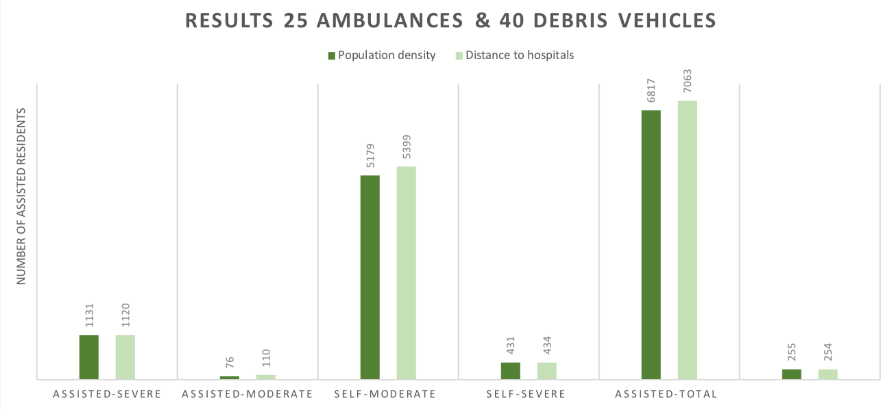
(b) Unreachable residents 25 ambulances 20 dozers

Figure 7.6: Results experiments 2 and 4

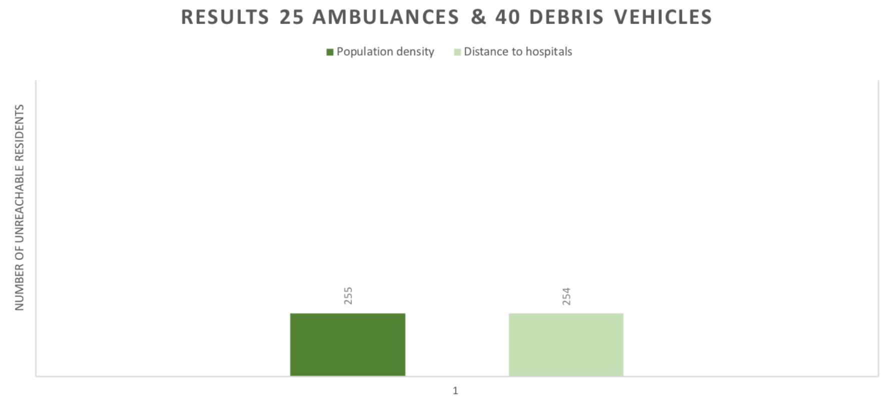
The figures above show that both debris removal strategies have a similar effect on the number of severely injured residents assisted in the simulation. However, the differences in the number of assisted individuals are not statistically significant when compared to the base case, which limits the ability to draw conclusions about their impact on this metric.

On the other hand, the number of unreachable residents significantly decreases with both strategies compared to the base case. This suggests that even when initial damage to the transportation network is relatively minimal, the strategic allocation of resources still plays a crucial role in enhancing accessibility. By efficiently targeting debris removal, more residents can technically be reached, if medical resources allow it, emphasizing the value of proactive resource management in emergency response scenarios.

Figure 7.7 shows the results for experiments 6 and 8, in which under the El Centro scenario, 25 ambulances and 40 dozers are operating within *Quakecity*.



(a) Assisted residents 25 ambulances 40 dozers



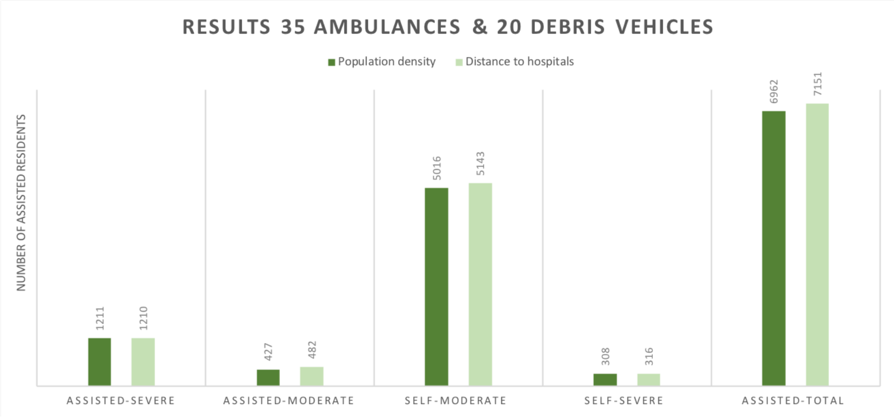
(b) Unreachable residents 25 ambulances 40 dozers

Figure 7.7: Results experiments 6 and 8

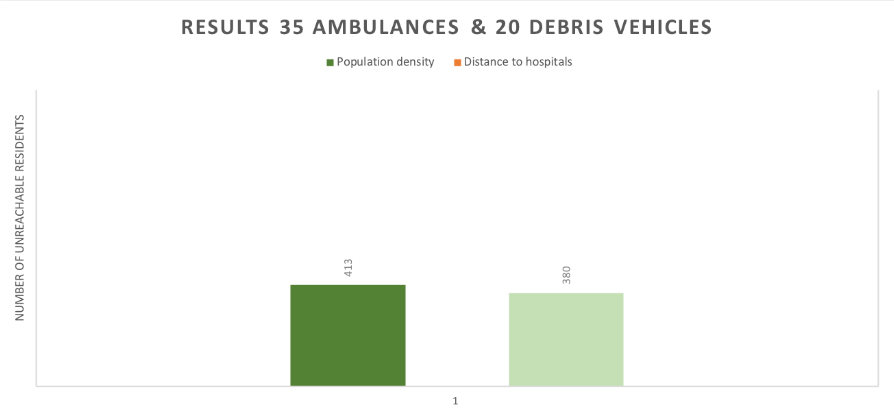
Unfortunately, these experiments do not show any significant impact on the number of assisted residents. This suggests that increasing the number of debris dozers in the El Centro scenario does not affect the number of people who can be assisted when ambulance capacity is limited. One possible explanation is that, given the available ambulance capacity, most injured residents are already reachable, even without additional debris removal efforts. This can be caused by the limited initial damage in the transportation network.

However, increasing debris removal capacity does have a significant effect on reducing the number of unreachable residents. Compared to experiments 2 and 4, the number of unreachable residents is halved when debris removal resources are increased. Specifically, there is a reduction of around 150 unreachable residents compared to the experiments with fewer debris removal resources.

Figure 7.8 shows the results for experiments 10 and 12, in which under the El Centro scenario, 35 ambulances and 20 dozers are operating within *Quakecity*.



(a) Assisted residents 35 ambulances 20 dozers



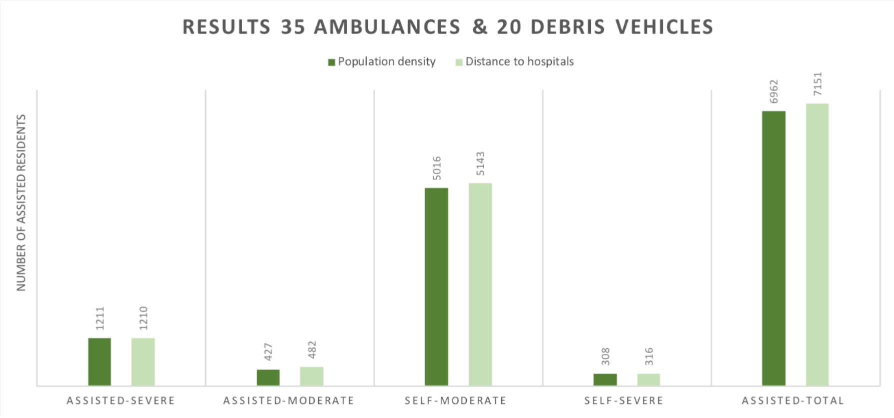
(b) Unreachable residents 35 ambulances 20 dozers

Figure 7.8: Results experiments 10 and 12

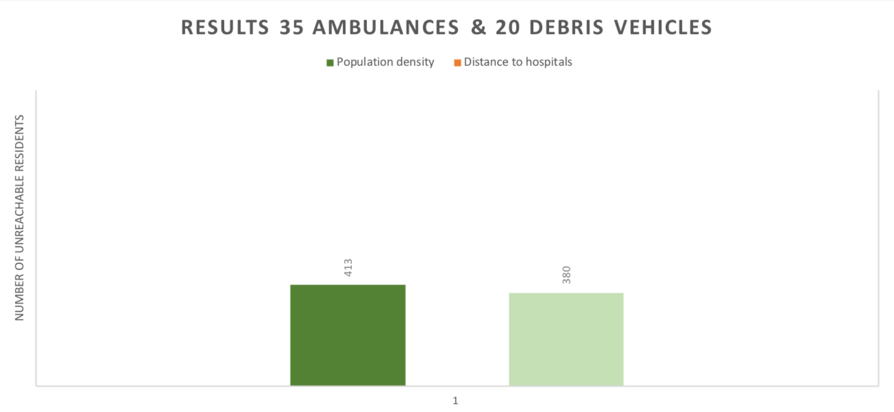
These results show a significant impact on the number of severely and moderately injured residents that can be assisted under the El Centro scenario. With an increase of around 200 compared to the base case, and an increase of 100 compared to experiments 2 and 4 for the severely injured residents and an increase of around 350 for assisting moderately injured residents for both debris removal strategies. These improvements in the severely assisted group likely reflect that many severely injured residents are already being reached in the base case and experiments 2 and 4. Therefore, adding more ambulances doesn't lead to a dramatic improvement in this group, because the remaining severely injured individuals are likely in areas that are still inaccessible due to the limited debris removal capacity. However, combining this increase with the big increase in the number of moderately people being assisted by ambulances shows the potential of increasing ambulance capacity, as with this increase suddenly more moderately injured residents can be assisted, as almost all of the reachable severely injured residents are already assisted.

However, similar to the results observed in the Kobe scenario, increasing ambulance capacity has no significant impact on the number of unreachable residents. This outcome is primarily influenced by the effectiveness of the debris removal strategies rather than the number of ambulances available.

Figure 7.9 shows the results for experiments 14 and 16, in which under the El Centro scenario, 35 ambulances and 40 dozers are operating within *Quakecity*



(a) Assisted residents 35 ambulances 40 dozers



(b) Unreachable residents 35 ambulances 40 dozers

Figure 7.9: Results experiments 14 and 16

Increasing both the ambulance capacity as well as debris removal capacity shows an increase in the number of severely injured residents who are assisted in the model. This suggests that increasing debris removal leads to more people being assisted, even with the same ambulance capacity of 35, and even in scenarios with less initial damage. Not surprisingly, the experiments also show a significant reduction in the number of unreachable residents. This number decreases to levels similar to those observed in experiments 6 and 8, where the number of debris dozers was also increased. Thus, for both ambulance capacities in the El Centro scenario, adding more dozers has a positive effect on reducing the number of unreachable residents.

However, adding more dozers in scenarios where ambulance capacity is already relatively high does not affect the number of people who go to the hospital on their own. This can be attributed to the fact that the extent of the initial damage plays a significant role in accessibility. In such cases, adding more dozers does not necessarily provide more opportunities for residents to reach the hospital independently.

7.5. Results of of deploying army vehicles

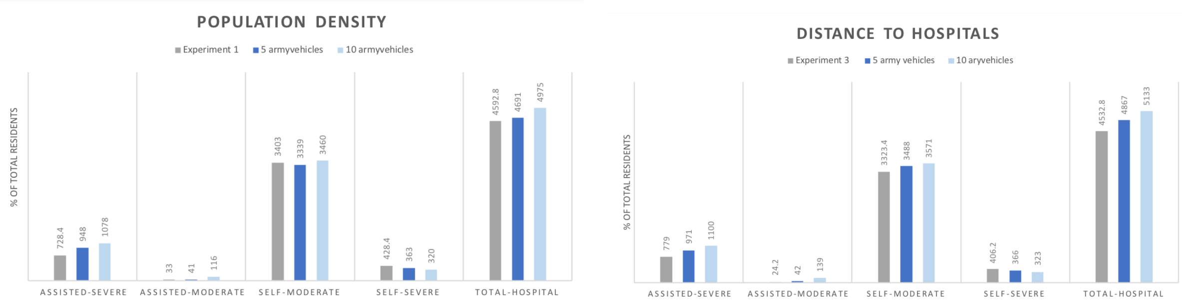
The result section of this study further explores the potential of deploying military vehicles as a contingency strategy for casualty transportation in post-earthquake urban environments. These vehicles are not designed to remove debris but rather to reduce the delays caused by road blockages, ensuring that injured residents can still be transported swiftly even when debris removal is incomplete.

To evaluate the impact of military vehicles on the overall effectiveness of the emergency response, a series of experiments were conducted. Given that the ”Kobe” scenario presented the greatest constraints on debris removal and casualty transportation, it was selected as the test environment for assessing the influence of military vehicles, like already elaborated in section 6.7.2.

In the first set of experiments (experiments 17 to 20), military vehicles were introduced to the experiments with limited resources for both debris removal and casualty transport, which are experiments 1 and 3. This setup reflects typical real-world conditions where disaster response capacity is constrained. Military vehicles are tested as a contingency measure to alleviate these constraints and provide a secondary means of casualty transportation when ambulances face delays.

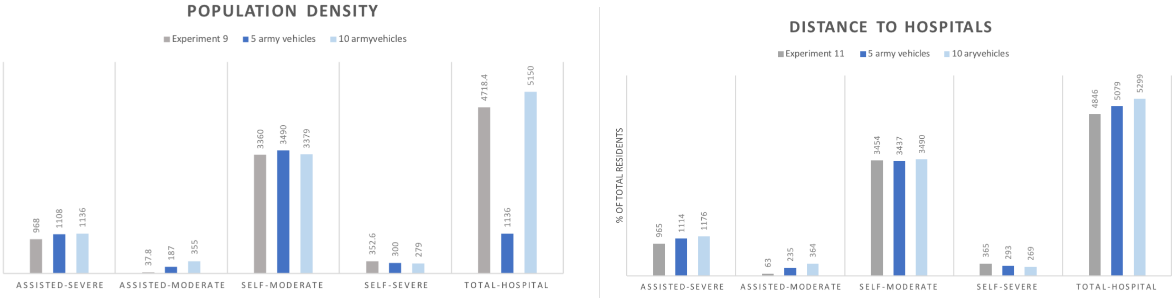
In the second set of experiments (experiments 21 to 24), military vehicles were tested in the experiments with increased ambulance capacity but still limited debris removal capacity, which are experiments 9 and 11. Here, the goal is to determine how military vehicles could serve as gap-fillers, bridging the delay in debris removal and ensuring continuous casualty transport. These experiments were conducted with 5 and 10 army vehicles, resulting in 8 additional simulations.

This section shows the results of the additional experiments in which the army vehicles are added to the model to complement the casualty transportation. As the additional army vehicles to not directly impact the unreachable residents, this section will focus solely on the assisted residents. Figure 7.10 shows the results of adding army vehicles to the experiments with limited resources, whilst Figure 7.11 shows the results of adding army vehicles to the experiments with increased ambulance capacity. The results are presented as the average result of all experiment runs.



(a) Impact of army vehicles under the population density strategy **(b)** Impact of army vehicles under the hospital strategy

Figure 7.10: Impact of army vehicles on the model results 25 ambulances & 20 dozers



(a) Impact of army vehicles under the population density strategy **(b)** Impact of army vehicles under the hospital strategy

Figure 7.11: Impact of army vehicles on the model results 35 ambulances & 20 dozers

These results highlight several insights regarding the addition of army vehicles to the earthquake response model. First, increasing the number of army vehicles consistently improves the number of residents assisted by ambulances, with 10 vehicles being more effective than 5. However, the impact of adding the first 5 army vehicles is more significant than the impact of adding an additional 5. This effect is particularly noticeable in scenarios where there are fewer ambulances available, suggesting that the benefit of army vehicles is greater when ambulance resources are limited.

Additionally, the distance to hospital strategy performs better when army vehicles are introduced, compared to the population density strategy. One interesting insight is that adding just 5 army vehicles in situations with constrained debris removal capacity has the same influence on improving outcomes as adding 10 ambulances, emphasizing the substantial role army vehicles play in reaching injured residents.

Notably, the deployment of army vehicles does not affect the number of residents who self-assist to hospitals. This is understandable, as the military vehicles do not improve road accessibility for the residents, since no debris is removed and no additional roads are cleared. The increased accessibility primarily benefits the military vehicles themselves, rather than the overall road network.

7.6. Summary of results

This section highlights the statistical significance of the results and provides an overview of all outcomes presented in the previous sections, expressed as percentages of each KPI relative to the total in their respective categories within the model.

7.6.1. Significance of results

The differences, both the increase and the decrease, between all experiments and the base case experiments are statistically significant. This means all experiments show a significant improvement, where expected, compared to base case experiments and ensure a more effective response.

However, to better understand the influence of the individual resource distribution strategies, increasing the number of dozers or ambulances, additional significance testing was conducted for each experiment. For instance, while an increase in both ambulances and dozers may significantly reduce the number of unreachable residents, it remains unclear whether this effect is driven primarily by the increase in ambulances, dozers, or a combination of both. Therefore, separate significance tests were performed to isolate and assess the impact of each variable individually, the results of these tests can be found in Appendix G. The presence or absence of significant impacts has already been discussed throughout the description and presentation of the results in the previous sections. However, this section will provide a concise, comprehensive overview of the results along with their statistical significance.

7.6.2. Overview of results

This section provides an overview of all the previous results in the form of the percentage of total residents that needed assistance which got assistance during the simulation. The A in the table refers to the number of ambulances, whilst the D refers to the number of dozers in the experiment and AV refers to the number of army vehicles. Table 7.2 shows the overview of the results under the Kobe scenario, whilst table 7.4 shows the overview of results under the El Centro scenario. **Bold text** in the table highlights the results that are statistically significant, indicating that the observed changes are driven by the experimental factor being adjusted. All p-values can be found in Appendix G.

Table 7.1: Clarification of letters in results tables

Letter	Meaning
A	Ambulance
D	Debris removal vehicles
AV	Army vehicles

Table 7.2: Results of assisted residents under the Kobe scenario

ID		Severe	Moderate	Self moderate	Self severe	Total
BC1	**Base case**	42.1%	0.2%	32.8%	24.0%	37.8%
	25A 20D					
1	Population Density	**43.1%**	0.3%	**33.4%**	**24.3%**	38.6%
3	Distance hospitals	**48.5%**	0.3%	**34.1%**	23.5%	**39.9%**
	25A 40D					
5	Population Density	43.5%	0.3%	34.7%	26.5%	40.1%
7	Distance hospitals	49.9%	0.4%	**39.5%**	**26.2%**	**45.1%**
	35A 20D					
9	Population Density	**57.5%**	0.5%	34.1%	**20.5%**	**41.0%**
11	Distance hospitals	**58.6%**	**0.9%**	**34.4%**	**20.4%**	41.7%
	35A 40D					
13	Population Density	**61.3%**	0.6%	**35.9%**	20.8%	43.1%
15	Distance hospitals	**63.3%**	1.0%	**39.2%**	21.2%	**46.6%**

Table 7.3: Results of assiste residents under the Kobe scneario and deployment of army vehicles

ID		Severe	Moderate	Self moderate	Self severe	Total
	Population density					
17	25A 20D 5AV	**55%**	0%	33%	21%	40%
18	25A 20D 10AV	**63%**	1%	34%	19%	42%
	Distance to hospitals					
19	25A 20D 5AV	**57%**	0%	35%	21%	41%
20	25A 20D 10AV	**64%**	1%	36%	19%	44%
	Population density					
21	35A 20D 5AV	**65%**	2%	35%	18%	43%
22	35A 20D 10AV	**66%**	4%	34%	16%	44%
	Distance to hospitals					
23	35A 20D 5AV	**65%**	2%	34%	17%	42%
24	35A 20D 10AV	**69%**	4%	35%	16%	45%

Table 7.4: Results of assisted residents under the El Centro scenario

ID		Severe	Moderate	Self moderate	Self severe	Total
BC2	**Base case**	61.2%	0.7%	43.3%	21.6%	49.5%
	25A 20D					
2	Population Density	**67.1%**	0.6%	48.3%	24.0%	54.9%
4	Distance hospitals	**67.7%**	1.1%	50.6%	24.1%	57.4%
	25A 40D					
6	Population Density	68.2%	0.8%	51.9%	26.0%	58.6%
8	Distance hospitals	67.6%	1.1%	54.1%	**26.2%**	60.7%
	35A 20D					
10	Population Density	**73.1%**	**4.3%**	50.3%	**18.6%**	59.8%
12	Distance hospitals	**73.0%**	**4.8%**	51.6%	**19.1%**	**61.5%**
	35A 40D					
14	Population Density	**74.9%**	4.6%	53.6%	19.5%	63.4%
16	Distance hospitals	**74.7%**	4.8%	54.0%	19.8%	63.9%

The results show clear trends across both the Kobe and El Centro scenarios. In both scenarios, the distance-to-hospitals strategy generally results in slightly higher percentages of assisted residents compared to the population density strategy, especially for severely injured individuals. The increase in ambulance and debris removal capacities leads to higher assistance rates.

In the Kobe scenario, increasing the number of ambulances significantly improves the number of assisted severe, whilst increasing debris removal units improves the number of self-assisted residents. The deployment of army vehicles further boosts these figures, especially in combination with the ”distance to hospitals” strategy, reaching up to 69% of severely injured residents being assisted by ambulances.

In the El Centro scenario, the less initial damage allows for higher overall assistance rates compared to Kobe. The increase in ambulance and capacities leads to substantial gains, with the ”distance to hospitals” strategy consistently showing slightly better results. Increasing the debris dozers only seems effective once the ambulance capacity is also plenty.

The initial number of unreachable residents per seismic scenario is presented in table 7.5. Thereafter the percentages of unreachable residents still unreachable after 3 days for the Kobe and El Centro scenario are presented in table 7.6 and table 7.7. The percentages per zone can be found in Appendix F.

Table 7.5: Initial number of unreachable residents

Seismic scenario	**Total**
Kobe	1569
El Centro	558

Table 7.6: Average percentage unreachable residents Kobe scenario

ID	Strategy	**Total**
BC1	**Base case**	72%
	20A 20D	
1	Population Density	72%
3	Distance to Hospitals	62%
	20D 40D	
5	Population Density	**50%**
7	Distance to Hospitals	**41%**
	35A 20D	
9	Population Density	**73%**
11	Distance to Hospitals	63%
	35A 40D	
13	Population Density	**55%**
15	Distance to Hospitals	**42%**

Table 7.7: Average percentage unreachable residents El Centro scenario

ID	Strategy	**Total**
BC1	**Base case**	69%
	20A 20D	
2	Population Density	**73%**
4	Distance to Hospitals	**70%**
	20D 40D	
6	Population Density	**46%**
8	Distance to Hospitals	**45%**
	35A 20D	
10	Population Density	74%
12	Distance to Hospitals	68%
	35A 40D	
14	Population Density	**50%**
16	Distance to Hospitals	**44%**

This overview clearly shows the impact the two strategies have on the number of unreachable residents. These results show that for both seismic scenarios, an addition of debris removal resources significantly impacts the number of unreachable residents. When debris removal resources are limited, there is a noticeable difference and more casualties are accessible when areas close to hospitals are prioritized. Overall the distance to hospitals strategy seems to outperform the population density strategy in terms of improvements in the total number of unreachable residents throughout the city.

8

Discussion

The outcomes of the modeling study presented in the previous chapters are reflected in this chapter. First, the results will be discussed in a more broad context and compared to other studies. Then the limitations of this study are evaluated. The goal of this chapter is to provide a critical perspective on the outcomes of the study.

8.1. Discussions of results

This section discusses the results even further. First, the impacts of the different resource availability's are presented. Thereafter, the impact of the allocation strategies are discussed. Lastly, a short discussion on the results of deploying army vehicles is presented.

8.1.1. Discussion of resource availabilities

Increasing the number of ambulances does not have a significant effect on the number of self-assisting residents or the number of unreachable residents. This can be explained by the fact that under the same debris removal recourse availability's, no extra roads are cleared compared to when the less ambulances are available.

However, increasing ambulance capacity does impact the number of residents that can be assisted in both seismic scenarios, whilst the relative impact is more severe in the Kobe scenario. Combining the higher availability of ambulances with a strategic distribution of debris removal resources causes the response effort to be more effective.

Increasing the number of dozers generally has a positive impact on the number of self-movers, as it improves road accessibility for residents compared to scenarios with fewer resources. As more debris is cleared, the road network becomes easier to navigate, enabling more residents to reach hospitals on their own. This increased accessibility is also reflected in the significant reduction in the number of unreachable residents throughout the city.

However, the effect of adding more dozers becomes truly noticeable only when plenty ambulance resources are available. In experiments with fewer ambulances, the ambulances themselves act as a bottleneck. This means that even with debris cleared, the ambulances remain constantly busy, picking up residents. In contrast, when there are more ambulances, they reach a point where the number of reachable residents is maximized. At this point, debris clearance begins to show statistically significant improvements in the number of residents assisted by ambulances. This can especially be seen in the Kobe scenario, as the additional debris removal resources are highly effective in reaching severely injured residents. However, in El Centro, the impact is less pronounced, likely due to the fact that the residents are already reachable, and the bottleneck in this scenario are the ambulances.

8.1.2. Discussion of debris removal strategies

For both debris removal allocation strategies, strategically distributing the resources shows better results than evenly distributing debris removal resources, even when resources are limited. These results highlight the importance of debris removal, even in the first phase of an earthquake response.

In the population density strategy, zones 1, 2, and 3 have access to more debris removal vehicles compared to other zones in the virtual city. However, due to their higher population density and crowded conditions, debris removal in these areas requires more careful handling, effectively reducing the overall removal capacity. With this is mind it is interesting to see whether the impact of this strategy is big because the clearance happens in areas where many injured residents are located, or if the impact is not as big as expected due to the decreased speed at which debris can be cleared from the roads.

In general the population density distribution strategy shows an improvement in the number of assisted residents throughout most experiments, implying it is better to prioritize these areas for debris removal compared to even distribution of resources. However, when both ambulances resources and debris removal resources are somewhat low, the impact of this strategy is solely evident in the El Centro scenario and the advantages of focusing on high-density areas decrease, as crowded conditions slow down debris removal efforts. The population density strategy also allows more residents to go to the hospitals by themselves, as cleared routes in high-density areas provide better accessibility. This is especially beneficial when debris removal resources are limited.

The population density strategy positively impacts the number of unreachable residents, but only when debris removal capacity is also increased. Without an increase in debris removal capacity, the strategy seems to have no significant effect. The strategy highly improves the reach ability of residents in zones 1, 2 and 3, which is logical as the resources are increased in these areas.

In the distance to hospitals strategy, zones 1, 3 and 8 have access to more debris removal vehicles compared to the other zones. In general, this strategy shows an improvement in number of assisted residents. Especially in the Kobe scenario, the impact of this strategy is evident. However, this is mainly seen when the debris removal resources are increased. This indicates that in highly constrained situations, clearing access to hospitals allows more efficient use of ambulances compared to the population density strategy. This could be caused by some areas surrounding the hospitals are damaged and need to be repaired before ambulance can operate normally.

When comparing the use of 20 versus 40 debris removal dozers under the same ambulance capacity, the results show a significant improvement in the transportation of severely injured residents. This highlights the positive impact of increasing the number of dozers, particularly when ambulance capacity is also expanded. However, when ambulance capacity is limited, adding more dozers—regardless of the allocation strategy—has no significant impact on the number of people who can be assisted. This suggests that, in the initial days following an earthquake, ambulance availability is more critical than increasing the number of dozers, across both seismic scenarios.
Overall, the distance to hospitals strategy appears to be more effective. However, it is difficult to determine whether this is due to specific zones having better access to resources or because densely populated areas face a reduction in capacity in the model. Notably, two out of three zones prioritized in the distance to hospitals strategy are also densely populated areas, and thus also face the reduction of debris removal capacity for the dozers operating in these zones. This suggests that clearing areas around hospitals is more effective, regardless of the capacity reduction in two of the zones.

The main difference between the two strategies lies in the capacity increase in zone 8, which, while not highly populated, is very close to multiple hospitals in the city. Despite its lower population density, zone 8 still has a significant number of injured residents, likely due to factors other than population density. Additionally, the presence of multiple hospitals in this zone likely contributes to the different impacts of the strategies, as improving access to several hospitals can significantly enhance the overall effectiveness of the emergency response.

8.1.3. Summary

Across the results, increasing the availability of debris removal resources generally has a greater impact than simply distributing them strategically. The influence of debris removal becomes even more pronounced in the Kobe scenario with higher initial damage, where clearing debris is critical to improving accessibility. Both strategies portray similar patterns of the impact on the number of people that can be assisted in experiments with lower levels of initial damage or when the availability of dozers is limited, although the overall effects are less dramatic in these cases. Additionally, the distance to hospital strategy significantly enhances the reachability of the affected area, as seen in the results where more residents can access hospitals compared to the population density strategy. Lastly, Army vehicles also prove to be highly effective, particularly when debris removal resources are constrained, as they help maintain mobility and access even in restricted conditions.

8.2. Positioning of research

This section compares the findings of this study with previous research in the field, highlighting areas of agreement or divergence compared to other studies.

This study focuses on simulating earthquake response whilst including debris removal efforts in the response phase. Its novelty lies in combining network recovery with the direct effect it has on the reachability of injured residents and the number of injured people who can be assisted. In this way, it integrates the mathematical approach typically used in network recovery analysis with a more practical approach through simulation. This study, unlike many others, emphasizes the importance of treating debris removal as a critical activity in urban earthquake response, rather than viewing it solely as a key component of earthquake recovery.

Overall, this study aligns with previous research by demonstrating the positive effects of debris removal on both reachability and accessibility within an urban network (Taghizadeh et al., 2023) (Özdamar et al., 2014). However, it extends this understanding by examining how debris removal positively affects the number of people who can be medically assisted, which is in their place linked to the amount of debris removal resources are available.

Some previous studies also address network recovery, though they often use different methods to prioritize which roads should be cleared. In line with studies by Sahin et al. (2016), Çelik et al. (2015) and Berktaş et al. (2016), this research emphasizes the importance of accessing critical nodes for an effective response effort. However, rather than focusing on a specific sequence of roads, this study takes a zonal approach for distributing resources, with hospitals being considered the critical nodes. As the results of this study showed clearing areas surrounding hospitals is more beneficial compared to immediately clearing densely populated areas.

In addition to examining debris removal strategies, this study highlights the positive impact of increasing ambulance capacity on the number of injured people who can receive assistance. This finding is consistent with the conclusions of Marasco et al. (2021) and Koch et al. (2020), despite the fact that different networks and city characteristics were analyzed in those studies. Moreover, this study expands on these findings by demonstrating that debris removal and increased ambulance capacity work together by further improving the assistance rate, complementing each other in enhancing emergency response effectiveness.

8.3. Limitations

"All models are wrong, but some are useful." This statement is true for any modeling study. Making a model can never be a direct representation of reality and therefore always comes with assumptions. It acknowledges that any created model will always fall short of the complexities of reality. The key is to create models in such a way that they can still be useful.

The model created for this research does not capture the entire complex dynamic environment of an earthquake response. The choices made in defining system boundaries scope the reality that this model represents. A model that can accurately represent all activities in an earthquake response is not a feasible idea. But, this is also not the goal, as we try to make a model which is useful.

This study aimed to create a model that could reflect on the impact certain debris removal strategies have on the effectiveness of an earthquake response, which in this study is the transportation of casualties to the hospitals. This system was simulated under different initial damage states and different resource availability's.

This study has been carried out with great care and effort, considering the time constraints. However, it is important to acknowledge several limitations that arise from the research approach and the simplifications made. Therefore, before drawing conclusions, this section addresses the main limitations of the study.

8.3.1. Limitations of method used

While ABM using NetLogo has been effective for the objective of this research, there are several limitations inherent in both the method and the programming platform. NetLogo, while user-friendly and ideal for rapid prototyping, is somewhat limited in terms of scalability and computational power. As the number of agents and interactions increases, performance can degrade. This was notable as the model contains calculations with the nw extension, which are related to graph theory. This in combination with the big network and many agents in the model, implementing certain conceptualized ideas was quite hard and challenging and sometimes more simplifications had to be made than desired. Given the current setup of the model, using Python could have been a more effective choice. However, due to time constraints and the author's limited experience with Python, NetLogo was chosen instead.

8.3.2. Limitations of model aspects

Assumptions made during the conceptualization, formalization and implementation of the model have an influence for the outcomes of this study. This section will reflect on some of the crucial assumptions and how they might affect the model outcomes.

Hospitals

One of the critical assumptions in this study is the exclusion of hospital capacity constraints, as the model assumes that hospitals have unlimited capacity to treat incoming patients. Or more specifically, dropped-off residents are assumed to be assisted. In reality, hospitals often face significant limitations in capacity during large-scale disasters like earthquakes. By not incorporating this factor into the model, the outcomes may overestimate the effectiveness of the emergency response. In practice, limited hospital capacity could result in delays in treatment, increased mortality rates, or a reduction in the number of people who can be assisted by ambulances.

Network model

Several assumptions are made to simplify the network within this model. One of these assumptions is that there is no other traffic on the roads. In reality, regular traffic and other emergency responders could significantly slow down the movement of ambulances and army vehicles. By not accounting for this, the model may overestimate the speed and efficiency of casualty transportation and debris removal. The lack of congestion or traffic delays in the model simplifies the system but does not fully reflect the real-world complexities of post-earthquake road usage.

Additionally, the model assumes that all road crossings are always open. In practice, intersections or crossings may also be blocked due to debris. This assumption likely underestimates the potential delays and rerouting that would be required in real earthquake scenarios, where blocked crossings could hinder the movement of ambulances.

Scope

The model is designed with a focus on urban areas using the building and road network of Turin. This geographical scope was chosen because calculations of the earthquake's impact have already been performed under specific seismic scenarios for this geographical area, making the model setup more valid compared to making various assumptions on the impact of earthquakes because of the time constraints in this thesis. However, this choice also has some limitations, since the model relies on specific building structures and seismic scenarios, its results are primarily applicable to cities with characteristics similar to the one modeled.

Despite these limitations, incorporating detailed urban characteristics has significantly enhanced the accuracy of the model and its environment, providing a more realistic simulation of earthquake dynamics and response efforts in densely populated areas. Additionally, the model can be adjusted to make it more suitable for other city simulations, whilst keeping the logic within the model.

Base model

The base model used as a reference case is somewhat based on the assumption that the debris removal resources are distributed evenly throughout the zones in the network once the emergency response starts. It is hard to say whether this is representative for a real-world situation or not, as in pre-planning of earthquake response there is no systematic way of distributing these resources from the minute an earthquake strikes. Therefore, comparing the proposed strategies of distributing the resources to this base model might not reflect a good overview of the actual impact. The model developed is more suitable for comparing the different strategies amongst each other, considering certain resource availability's.

Time

In this study, each tick represents one minute. The routing and transportation of the ambulances and the army vehicles is modeled in such a way that in eah tick they move over a link in the graph from one node on the route to the next node on the route. However, this assumption implies that all links are of equal length, which is not reflective of real-world road networks where distances between points can vary significantly. Traveling over short links will probably take less than a minute, whilst travelling over some of the longer roads will likely take longer. With this in mind, the model simplifies the transportation process. This way of modeling might results in overestimating the number of people that can be assisted by the casualty transporters.

Earthquake scenarios

Using two specific benchmark earthquake scenarios in this study provided a controlled environment for assessing the different debris removal strategies under defined conditions, such as road blockages and the distribution of injured residents across the transportation network. This approach allows for a detailed analysis of how the modeled system behaves in these specific contexts, offering valuable insights into the effectiveness of casualty transportation and debris removal within these particular scenarios.

However, relying two benchmark scenarios also limits the possibilities of generalizing the findings of this study. Like already mentioned in chapter 3, earthquake impacts vary greatly depending on factors like the geographical layout, building densities, road networks, and the scale of the disaster. The specific road blockages and injury distributions modeled in the road transportation network here may not fully represent the range of possible conditions in other earthquake scenarios. Therefore, while these results provide useful insights, they may not capture the broader context of urban areas under varying earthquake conditions.

Injured residents

Furthermore, the input variables for the benchmark scenarios are based on the average of three scenarios calculated by (Battegazzorre et al., 2021) throughout different times of the day. By averaging these scenarios, the model is able to capture a broader perspective of how injuries might be distributed, rather than focusing on a single, time-specific scenario that may not be reflective of overall patterns. This means the results of the model show an indication of the effects of the different debris removal strategies on the effectiveness of the response.

However, while averaging across scenarios helps to create a more generalized input for the model, it also has some limitations. Real-world earthquake impacts can vary significantly depending on the time of day, especially in terms of population exposure (e.g., during work hours vs. nighttime). This should be taken into account if the results are used.

Debris removal

Firstly, in the model, debris is simplified to represent solely debris from buildings, while the debris removal resources are simplified to bulldozers capable of clearing all debris in the model. In reality, debris from an earthquake can be much more varied. Moreover, different types of debris require specific equipment for clearing the debris to make the road accessible. For example, heavy machinery like cranes, may be needed when large structural debris is blocking roads. This simplification allows for a more streamlined simulation, but it does not capture the full complexity and logistical challenges of real-world debris management, where various debris and equipment are in place. Future models could incorporate different debris types and different removal equipment to get more insights.

Secondly, the process of debris removal is simplified by allowing the debris dozer to target and begin clearing any blocked road, given the city zone the dozer is operating in, even if the surrounding roads are also blocked and inaccessible. This assumption creates a scenario where the dozer can clear isolated sections of roads that, in reality, would not be reachable without first clearing the surrounding area. By allowing debris dozers to target any blocked road without considering the surrounding blockages, the model simplifies the operational challenges and may present a more optimistic view of how quickly road networks can be restored.

Army vehicles

In this model, army vehicles were incorporated to assist in the transportation of casualties, under the assumption that these vehicles would be available and suitable for this purpose. However, in reality, this assumption may not hold true in all cases. Army vehicles are not always equipped for medical transport, lacking necessary equipment such as stretchers or life-support systems that are standard in ambulances. Additionally, these vehicles might be allocated to other critical tasks during an emergency, such as logistical support, security, or large-scale debris removal. This potential limitation suggests that while army vehicles can enhance emergency response in the model, practical constraints may limit their actual effectiveness in real-world scenarios.

However, in disaster scenarios, where the overall goal is to save as many lives as possible and reduce the impact, the absence of specialized medical equipment may be less of a limiting factor. While army vehicles may not be ideal for the most extreme injuries requiring immediate medical attention, they could still play a big role in transporting severe or moderate injured.

9

Conclusion

This final chapter concludes the research with a reflection on the contributions of this research and the recommendations for future research. First an overview of the main research findings are presented, which answers the main research question. Next, the scientific contributions and the contributions to disaster management are explained. Finally, recommendations for future research are made.

This study has aimed to bridge the gap between the limited integration of debris removal in the emergency response phase and the impact it can have on a response. Previous research primarily focused on network recovery and mathematical models for debris clearance, often neglecting the influence of debris removal on other critical emergency response activities. Therefore, the objective of this study was to explore various debris removal strategies during phase 1 of earthquake response and assess their impact on the overall success of emergency operations at the urban scale and thereby answering the main research question:

What is the influence of various debris removal strategies on the effectiveness of a post-earthquake emergency response in urban areas?

9.1. Answering the research questions

To achieve the objective of this research and answer the research question, this research started with an analysis of the current system environment for earthquake response in urban areas with a focus on the following activities: casualty transportation and debris removal. This analysis has been performed using disaster management literature and governmental reports covering the responses of previous earthquake events in urban areas.

In general, the current system environment for earthquake emergency response in urban areas involves a complex coordination of multiple actors. Key actors include authorities, NGOs, the local community, and emergency services, each playing a vital role in managing the immediate response. Authorities oversee coordination and resource allocation, while NGOs and local communities assist with relief and support. Debris removal is essential to the system, as blocked roads hinder rescue operations and casualty transportation. Debris management teams and contractors work to clear routes using heavy machinery, enabling access for emergency services. However, the institutions and guidelines in the system do not cover the way debris removal should be handled from minute one. Casualty transportation is handled by ambulances, supported by hospitals that must quickly expand capacity to treat the influx of patients. Ambulances often navigate blocked roads to reach casualties, and in some cases, the military assists with transportation when civilian resources are strained. Urban areas typically have better access to resources, including more hospitals and specialized emergency services, but high population density and infrastructure damage can slow down response efforts. Once routes are cleared, many residents also transport themselves to hospitals. Overall, the system relies on efficient coordination between debris removal and emergency services to ensure timely medical care for affected individuals.

This research continued by exploring the meaning of effectiveness in the context of an earthquake response by conducting a literature review. From this literature review it was found that the effectiveness of an earthquake emergency response can be measured using two primary approaches: patient outcomes and response times. Patient outcomes focus on metrics such as the number of injuries treated, lives saved, and mortality rates, reflecting the overall impact of the response on human lives. Response times, on the other hand, quantify the efficiency of the emergency response, including the speed of ambulance dispatch and time to deliver medical care. Additionally, in cases where debris removal is part of the response phase, the progress of clearing debris and network accessibility also serves as a measure of effectiveness, although this is more commonly applied in recovery phases.

An agent-based model was conceptualized and formalized that models casualty transportation in an urban area, whilst including debris removal operations to clear the obstructed roads in the city network. The model is evaluated using two key metrics: the number of assisted residents, which reflects patient outcomes, and the number of unreachable residents, which indicates the progress of debris removal and overall accessibility. These metrics together provide an assessment on how the strategies influence the response.

This study tested two different resource distribution strategies for debris removal, based on different geographical zones within the city. In addition, this study has shown the impact of deploying army vehicles as casualty transportation as a supplementary strategy.

The population density strategy prioritizes clearing debris in densely populated areas, where the demand for immediate assistance is expected to be high due to the large number of residents. This approach has consistently demonstrated improved outcomes in assisting residents across several experiments, suggesting it is more effective for allocating debris removal resources than distributing them evenly across a city. By clearing routes in high-density areas, the strategy enables a larger number of injured residents to self-transport to hospitals, as accessibility improves. However, this is only evident when initial damage is severe. In addition, this positive impact increases if debris removal resources are also increased.

This strategy is especially effective when both ambulance capacity and debris removal resources are high, as the combination significantly enhances the assistance rate. However, when ambulance capacity is low, even if debris removal resources are high, the bottleneck shifts to the availability of ambulances. In such cases, the extra debris removal capacity cannot be fully utilized, as the limited ambulance availability prevents timely assistance. This dynamic is evident in both seismic scenarios analyzed in the study.

The Distance to Hospitals strategy focuses on removing debris in areas that are on average closest to hospitals, regardless of population density. The benefits from this strategy become significantly evident in the more severe seismic scenario, especially when debris removal capacity is increased. This is reflected in an increase in the number of severely injured residents assisted, particularly when comparing scenarios with 20 to 40 debris removal vehicles.

This strategy is also especially effective when both ambulance capacity and debris removal resources are high, similar to the population density strategy. In experiments with more ambulances, this strategy performs well. This indicates that in highly constrained situations, clearing access to hospitals allows more efficient use of ambulances compared to the population density strategy. This could be caused by some roads surrounding the hospitals being damaged and need to be cleared before the ambulances can operate normally. The strategy also shows a positive impact on self-transport residents, as cleared routes around hospitals allow more residents to reach medical care independently. When ambulance capacity is limited, the benefit of this strategy is reduced, though still positive. However, this strategy tends to concentrate resources in areas close to hospitals, potentially leaving out distant, high-population areas where residents may require urgent assistance but have fewer resources allocated.

When comparing the population density and distance-to-hospital strategies, both show a similar impact on assisting residents in the scenario with less initial damage. However, the distance-to-hospital strategy performs better in more constrained situations, as it prioritizes clearing routes to hospitals, which improves accessibility for injured individuals who need assistance. For self-transporting residents, the distance-to-hospital approach also proves more effective. Additionally, both strategies show a positive impact on the number of unreachable residents if debris removal resources are increased, although the impact of the distance to hospital prioritization strategy is bigger for both seismic scenarios.

Deployment of army vehicles to the earthquake response model provides several key benefits. Increasing the number of army vehicles consistently enhances the number of residents assisted by ambulances, with 10 vehicles being more effective than 5. However, the initial deployment of 5 vehicles has a more pronounced impact compared to adding an additional 5, especially when ambulance resources are limited. Moreover, the distance-to-hospital strategy outperforms the population density strategy when army vehicles are incorporated. Notably, introducing just 5 army vehicles significantly improves outcomes even in scenarios with limited debris removal capacity, emphasizing the possibilities of these vehicles in constrained environments.

So to conclude, earthquake response remains a highly complex and intertwined environment and although increasing ambulance capacity has more influence than clearing access to casualties, this study has shown that debris removal can significantly improve the process of casualty transportation under different resource availability's, particularly in earthquake scenarios with higher levels of damage. The impact of strategically distributing debris removal vehicles shows a positive impact on both the number of people who are assisted as well as the number of people who are still unreachable. However, this impact is most significant when more debris removal resources are available. When resources are limited, the influence of strategic distribution decreases considerably, suggesting that its added value is questionable in low-resource scenarios. This raises the point that, under resource-constrained conditions, the effectiveness of a strategy alone may not be sufficient to substantially improve outcomes. In addition, this study showed that using army vehicles as casualty transporters has a significant positive effect regarding the assistance of injured people, showcasing its potential for future earthquake response efforts even when resources are constrained, mitigating the impacts of the previously explained resource-constrained conditions.

9.2. Contributions of this research

9.2.1. Scientific contribution

This research makes several scientific contributions to the field of earthquake response and debris clearance. First, in line with existing literature, it highlights the importance of clearing areas close to important places, in this case hospitals, as key points in the response network that must remain accessible to ensure an effective response.

This study contributes to the database of models that exist that include debris removal as an activity in an earthquake response operation. The study emphasizes the importance of incorporating debris removal as part of the response phase, rather than focusing solely on the recovery phase, contributing to ongoing discussions in the field that recognize the vital role debris clearance plays in enabling emergency services. Additionally, this work extends the literature by showcasing the direct impact of debris removal on saving lives and improving the reachability of casualties, moving beyond more common mathematical analyses that focus on network connectivity or centrality. By demonstrating how debris clearance influences the speed and effectiveness of casualty transportation, this research provides a more practical perspective on how debris management affects real-world outcomes. Furthermore, although the model is designed around a specific network and earthquake environment, the rules and framework of the model can be adapted to model similar scenarios in different contexts, allowing for model re-usability and expanding its potential application in various urban or disaster-prone areas.

9.2.2. Contribution to disaster management

This research contributes to the disaster management sector by demonstrating the importance of starting debris removal operations immediately after an earthquake and strategically deciding where to allocate resources. It highlights that zone characteristics, such as population density or proximity to hospitals, can be used as a debris removal strategy, which can be incorporated into pre-disaster plans. Even when the full extent of the damage is unknown, initiating debris removal based on known factors before an earthquake strikes can help save lives by ensuring faster access to emergency services. As more detailed information becomes available in the days following the earthquake, this strategy can be adapted to optimize response efforts, but having a proactive plan in place from the outset improves the overall effectiveness of the response.

In addition to emphasizing the importance of early and strategic debris removal, this research also highlights the added value of using military vehicles for casualty transportation in earthquake response. Military vehicles, with their ability to traverse difficult terrain and bypass blocked routes, offer an advantage in reaching casualties in areas that are otherwise inaccessible. This insight suggests that integrating military resources into disaster response plans can enhance the speed and efficiency of casualty transportation, especially in the critical early hours after an earthquake, when road blockages are most severe. By demonstrating the superior effectiveness of this approach, the research contributes valuable knowledge for disaster management strategies that aim to maximize life-saving efforts with limited resources.

9.3. Recommendations for future research

This thesis tried to explore different debris removal strategies during an earthquake response in urban areas and evaluate the impact these strategies have on the response and accessibility. The outcomes increase knowledge of the importance of incorporating strategic resource use in these circumstances. Even though disaster management and earthquake response is a well-researched research domain, there is still so much left to explore about the dynamics of an earthquake response and how debris removal can be integrated into this phase.

9.3.1. Response activities

One direction for future research could be by expansion of the current model by incorporating additional emergency response activities, particularly search and rescue operations. While the present model focuses primarily on debris removal and casualty transportation, the inclusion of search and rescue would provide a more comprehensive understanding of post-disaster response dynamics. The current model only models injured residents, and trapped residents are not considered. Search and rescue plays a critical role in locating and assisting trapped or missing individuals and search and rescue operation are a big part of the overall success of a response effort, especially in densely populated areas where structural collapse is more likely. Integrating trapped individuals into the model could be an interesting study to research to what extend trapped individuals delay debris removal efforts in phase 1.

9.3.2. Expanding debris removal

Another direction for future research, that would further strengthen the model is expand the model by introducing different types of debris and the specific equipment required to clear each type. By introducing different types of debris and equipment into an urban environment, more accurate insights can be found for the complexities of post-earthquake response, and this could also improve strategic resource allocation. This enhancement would also allow for more detailed assessments of how equipment shortages or bottlenecks affect the overall effectiveness of emergency response efforts.

9.3.3. Army vehicles

As the results of the model demonstrate the potential benefits of using army vehicles for casualty transportation, future research is suggested to explore the practical feasibility of these findings. This includes assessing the logistical, operational, and technical challenges involved in using military vehicles for medical transport. Research should also evaluate the extent to which army vehicles can transport severely injured residents requiring medical attention en route. By addressing these practical considerations, future work could provide valuable insights into whether army vehicles can be a reliable and scalable solution for urban disaster scenarios.

9.4. Policy Recommendations

As the results indicate the importance of debris removal in terms of earthquake response the following policy recommendations are in place for local authorities of cities in earthquake-prone areas.
Pre-planning is essential for effective disaster response. Thus, local authorities of cities in earthquake-prone areas should try to include more thought through debris removal planning in this pre-planning. This would be of great value, as this can impact the number of lives that can be saved. So it could be valuable to use the zoning strategy to make a pre-disaster resource allocation plan, based on high-risk areas based on historical earthquake impact data and road blockages. Knowing where to deploy debris removal resources based on this zoning, focusing on critical zones in the early response stage. Mainly because this can help with the immediate deployment of debris removal vehicles in certain areas, before knowing the full extent of the damage and the exact places where they are most needed.

In addition to carefully selecting areas for initial debris removal in urban disaster planning, establishing pre-arranged contracts with contractors can significantly speed up the process. Contractors, who are often responsible for operating heavy machinery during debris removal operations, can be mobilized more quickly if agreements are in place beforehand. This proactive approach ensures that necessary equipment and manpower are readily available. Early collaboration with contractors not only enhances logistical efficiency but also strengthens overall disaster preparedness efforts, resulting in more efficient execution of the pre-disaster plans.

Army vehicles can play a critical role in disaster response, particularly in the initial stages. Incorporating them into response plans ensures rapid deployment where needed most, though their use should be carefully balanced, as these vehicles are often required in multiple locations and are used for various response activities. However, given that saving lives is the primary objective of a response effort, using these vehicles for casualty transportation seems like a good option to improve the overall initial response in cities. Given the slower pace of debris removal in densely populated areas due to debris and narrow roads, it is recommended to deploy army vehicles in these zones, as these roads take longer to clear.

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A

Appendix A

Table A.1: Modeling assumptions

Category	Assumption	Justification
Buildings	Buildings have a number of residents	Based on data set
	Buildings have number of moderately and severely injured people	Based on data set
	One crossing represents all buildings that are closest to that crossing	Simplification of the model
Hospitals	Hospitals have unlimited capacity	Simplification
	Hospitals are the endpoint of casualty transportation	
Residents	All residents are inside buildings	Based on data set used
	Residents are honest about the severity of their injury	Simplification
	Residents are either on a crossing or in the ambulance or hospital	Simplification
	Residents have to call 112 in order to be reported to the global state as injured	
Network	Transportation network is assumed to be an undirected graph	Assumed that directions are not relevant in case of an earthquake emergency
	Roads are either blocked or not blocked	based on valid damage assessment data
	There is no other traffic on the roads	Simplification
	Crossings are always open	Simplification
	Hospitals are placed on crossings, the breed is changed to hospital	
	Roads report themselves	Based on damage assessment
Casualty transporter	Ambulances prioritize severely injured residents	Based on literature
	Have a capacity of 1	Based on literature
	Move through the network from crossing to crossing	Simplification
	Army vehicles can drive over roads not yet accessible for ambulances	
	Different threshold represents road accessibility for ambulances and army vehicles	
Debris	Longer roads have more volume of debris	Based on calculations
	Debris is assumed to be one type of debris	Simplification
Debris removal vehicles	Have a certain removal capacity based on the population density of the zone	to account for the more challenging debris removal in dense areas
	Assumed to operate within the zone they are located in	Simplification for resource distribution

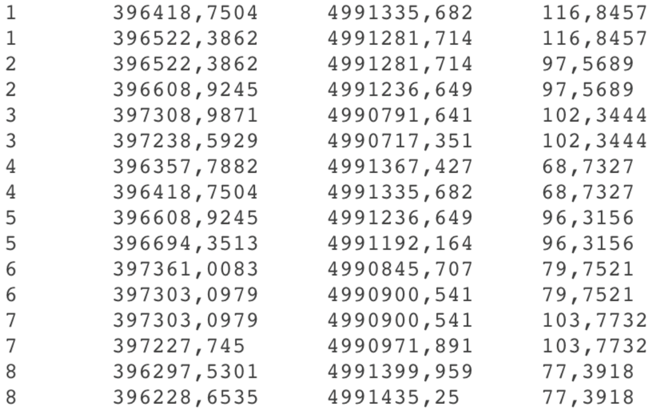
B

Appendix B

This appendix shows the nature of the data used in the formalisation of the model.

B.1. Network Data

To create the network in netlogo, a datafile is used which is modified in excel to make it suitable for Netlogo to read using the csv extension. A snapshot of the original file is shown in figure B.1.

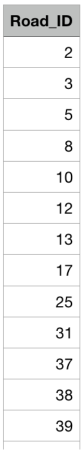


```
1       396418,7504     4991335,682     116,8457
1       396522,3862     4991281,714     116,8457
2       396522,3862     4991281,714     97,5689
2       396608,9245     4991236,649     97,5689
3       397308,9871     4990791,641     102,3444
3       397238,5929     4990717,351     102,3444
4       396357,7882     4991367,427     68,7327
4       396418,7504     4991335,682     68,7327
5       396608,9245     4991236,649     96,3156
5       396694,3513     4991192,164     96,3156
6       397361,0083     4990845,707     79,7521
6       397303,0979     4990900,541     79,7521
7       397303,0979     4990900,541     103,7732
7       397227,745      4990971,891     103,7732
8       396297,5301     4991399,959     77,3918
8       396228,6535     4991435,25      77,3918
```

Figure B.1: Snapshot of data for the network

The file consist out of the following information. Each road has two lines in the data set. The first row consists out of the road_id, the x coordinate of endpoint1, the y coordinate of endpoint and the length of the road. The second row consist out of the road_id, x coordinate of endpoint 2, the y coordinate of endpoint 2 and the length of the road. This data has been modified in a way that one row represents all the information on one road. This made it possible to let Netlogo read the file with some coding to create the network.

The setup of the model also incorporated the initial blocked roads. A data file has been used that contains the road_id's of the roads that are blocked under a certain benchmark scenario. This means a different file is used for both of the seismic scenarios used in this study. A snapshot of the data is shown is figure B.2.



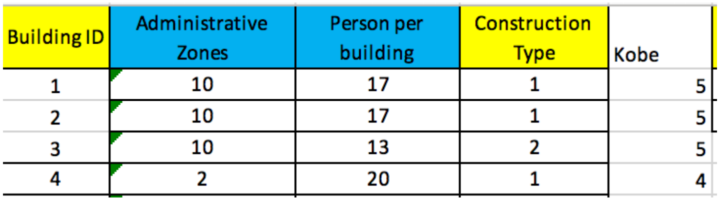
Road_ID
2
3
5
8
10
12
13
17
25
31
37
38
39

Figure B.2: Snapshot of data for blocked roads

B.2. Injured residents

For formalising the distribution of injured residents, a data file is used which calculates the probabilities of injured residents in each building based on the damage state of the building after a certain seismic scenario occurs. This section will shortly explain how this works.

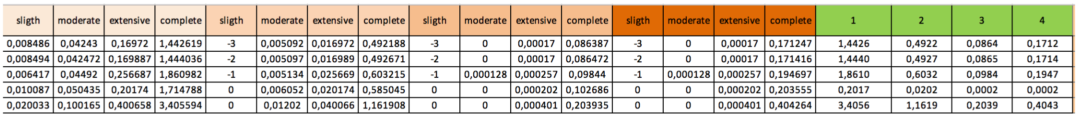
First, Marasco et al. (2021) used the different seismic scenarios in simulation using the data of the virtual city, which resulted in the determination of damage states for each building. These damage states range from no damage to complete damage and were then applied to the dataset containing information about the buildings, including the number of occupants and construction types. Based on these damage states, the number of injured people per building was calculated and categorized into four levels: slightly injured, moderately injured, severely injured, and death. For the model, only the moderate and severe injury categories were used. The final injury estimates for each building were transformed into a csv file and integrated into the NetLogo model which allows the model to create the injured residents at the right locatiosn in the model .
Figure B.3 shows the first stage of the data file in which the building, number of people per building, the construction type of the building and the damage state under in this example the "Kobe" scenario.



Building ID	Administrative Zones	Person per building	Construction Type	Kobe
1	10	17	1	5
2	10	17	1	5
3	10	13	2	5
4	2	20	1	4

Figure B.3: Snapshot of injured residents phase 1

Figure B.4 shows the second phase of calculating the injured residents per building. For each damage state of each building a different probability is used to calculate the number of average injured residents for the 4 injury severity levels. Then the information of the damage state of each building under a certain seismic scenario is used to finalize the number of injured residents in each building.



sligth	moderate	extensive	complete	sligth	moderate	extensive	complete	sligth	moderate	extensive	complete	sligth	moderate	extensive	complete	1	2	3	4
0,008486	0,04243	0,16972	1,442619	-3	0,005092	0,016972	0,492188	-3	0	0,00017	0,086387	-3	0	0,00017	0,171247	1,4426	0,4922	0,0864	0,1712
0,008494	0,042472	0,169887	1,444036	-2	0,005097	0,016989	0,492671	-2	0	0,00017	0,086472	-2	0	0,00017	0,171416	1,4440	0,4927	0,0865	0,1714
0,006417	0,04492	0,256687	1,860982	-1	0,005134	0,025669	0,603215	-1	0,000128	0,000257	0,09844	-1	0,000128	0,000257	0,194697	1,8610	0,6032	0,0984	0,1947
0,010087	0,050435	0,20174	1,714788	0	0,006052	0,020174	0,585045	0	0	0,000202	0,102686	0	0	0,000202	0,203555	0,2017	0,0202	0,0002	0,0002
0,020033	0,100165	0,400658	3,405594	0	0,01202	0,040066	1,161908	0	0	0,000401	0,203935	0	0	0,000401	0,404264	3,4056	1,1619	0,2039	0,4043

Figure B.4: Snapshot of injured residents phase 2

B.3. Characteristics of cityzones

In order to divide the zones in groups based on certain characteristics some calculation have been made. Table B.1 shows the population density of each zone.

Table B.1: Population density in zones

Zone	Pupulation density
Zone 1	9530
Zone 2	12379
Zone 3	10940
Zone 4	8133
Zone 5	8712
Zone 6	5905
Zone 7	7388
Zone 8	4886
Zone 9	5321
Zone 10	4704

The average distances from each zone to the hospitals is calculated using the nw extension in Netlogo. Where is is possible to find the shortest route to each of the hospitals from the midpoint of each zone. These distances are shown in meters in table B.4.

Table B.2: Average distance to hospitals for each zone

Zone	Average distance to hospitals
Zone 1	3149
Zone 2	4924
Zone 3	3997
Zone 4	4096
Zone 5	5963
Zone 6	6532
Zone 7	4431
Zone 8	3410
Zone 9	5493
Zone 10	7724

Table B.3 and B.4 present the different debris removal resource allocations for both the debris removal strategies.

Table B.3: Dozer allocation for limited resource availability

	Population density	Distance to hospitals
Zone 1	3	4
Zone 2	4	1
Zone 3	3	4
Zone 4	2	2
Zone 5	2	1
Zone 6	1	1
Zone 7	2	1
Zone 8	1	4
Zone 9	1	1
Zone 10	1	1

Table B.4: Dozer allocation for increased resource availability

	Population density	**Distance to hospitals**
Zone 1	9	9
Zone 2	9	3
Zone 3	9	9
Zone 4	3	3
Zone 5	3	1
Zone 6	1	1
Zone 7	3	3
Zone 8	1	9
Zone 9	1	1
Zone 10	1	1

C

Appendix C

Table C.1: Model

Name in code	Definition	Value/range	Source
Number-hospitals	Number of hospitals located in the virtual city	8	(Ardagh et al., 2012) (Battegazzorre et al., 2021)
Initial-ambulance-search-radius	radius in which ambulance target patient	300	Based on 1/3rd of the map
Ambulance-reroute-frequency	defines how often ambulance update their route	60	xoccurs every hour
Probability-to-call-112	Probability injured residents call 112	0.04	Own specification
Amount-debris-dozers in zone	Number of debris dozers in base scenario	20	Own specification
Roads-report	Number of roads that are assessed	400	Own specification
Amount-army vehicles	Number of army vehicles in the model	0	-
Army-vehicle-reroute-frequency	Defines how ofter army vehicles update their route	60	occurs every hour

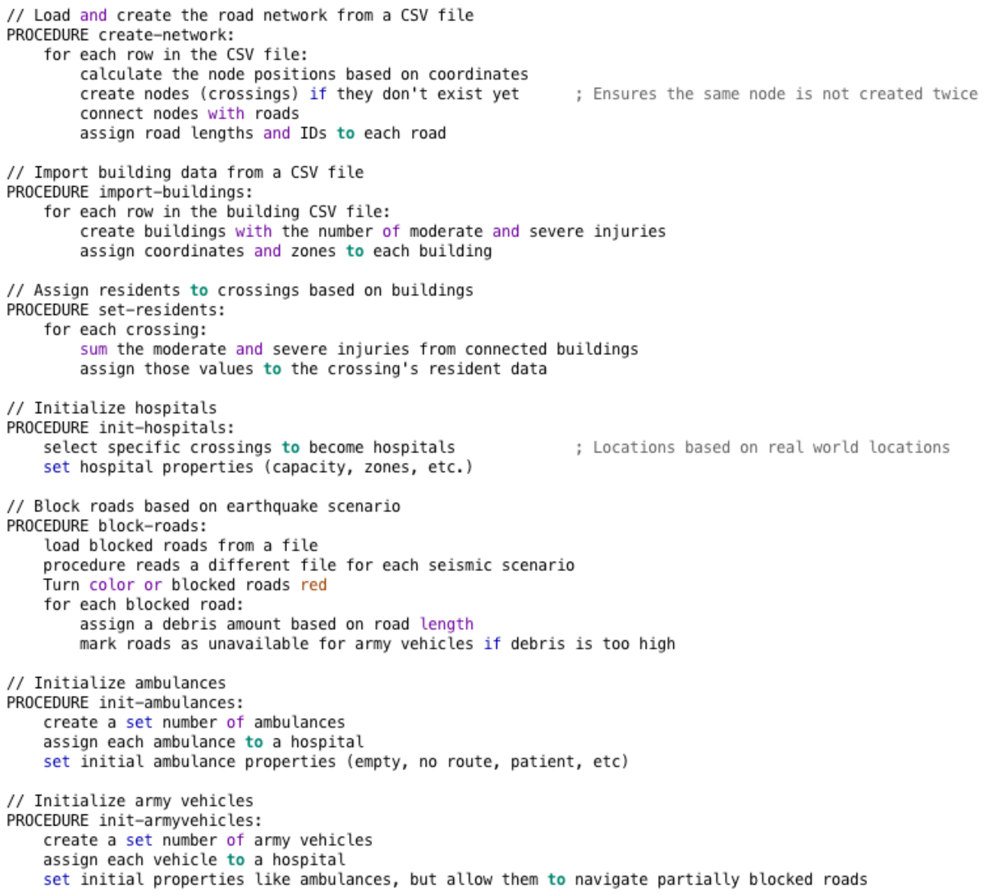
Table C.2: Variables

Name in code	Variable	Definition	Value/range
Health	Health level	Health level of the injured resident	[0-100]
Health_status	Health status	Health status of the injured resident	[Moderate, Severe]
Medical-treatment	Medical treatment	Indicates what treatment resident is receiving to update health accordingly	[]
Reported?	Reported	Identified whether a injured residents is reported as injured	True/False
Help-underway	Help underway	Defines whether an ambulance has targeted this resident	True/False
Cityzone	Cityzone	Defines the cityzone of the the crossing	1-10
Road-zone	Roadzone	Defines the cityzone of a road	1-10
Target-road	Target road of debris dozer	Defines the target road of the debris removal vehicle	road_id
Destination	Destination of ambulance	Defines the crossing or hospital the ambulances wants to go to	crossing number
Route	Route of casualty transporter	Defines the sequence of crossing on the route to the destination	False, (crossing,.. crossings..
Full?	x	Defines whether a casualty transporter is transporting a patient	True/False
Enroute?	x	Defines whether a casualty transporter is moving	True/False
Patient	injured resident	defines the patient the casualty transporter is transporting	resident number
Moderate_injuries	Moderate injuries	number of moderate injuries on crossing	from connected buildings
Severe_injuries	severe injuries	number of severe injuries on crossing	from connected buildings
Injuredresident	injured resident	number of total injuries on crossing	severe + moderate
Reachable?	reachable	defines whether a crossing is reachable from the hospital	True/false
Node$_{i}d$	crossing id	defines the crossing id	read from csv file
Road_length	road length	length of the road	read from csv file
road$_{i}d$	road id	defines the road id of the road for blockages	read from csv file
Debris	Debris on road	defines the amount of debris	1-2000
Assessed?	road assessed	defines whether a road is known to be blocked	True/false
Availableforarmy?	threshhold	defines whether a road can be used by army vehicles	True/false
Building_id	building id	used in the setup of the model	number
Number_moderate	number moderate injuries	number of moderate injuries in building	read from csv file Number_severe
number severely injuries	number of severe injuries in buildin	read from csv file	
Connected_id	building connected id	crossing id of nearest crossing	number
Target_road	target road	defines the road that is targeted by the debris dozer	road id of target road
Partofnetwork	part of network	defines whether an object is part of the network	True/false

D

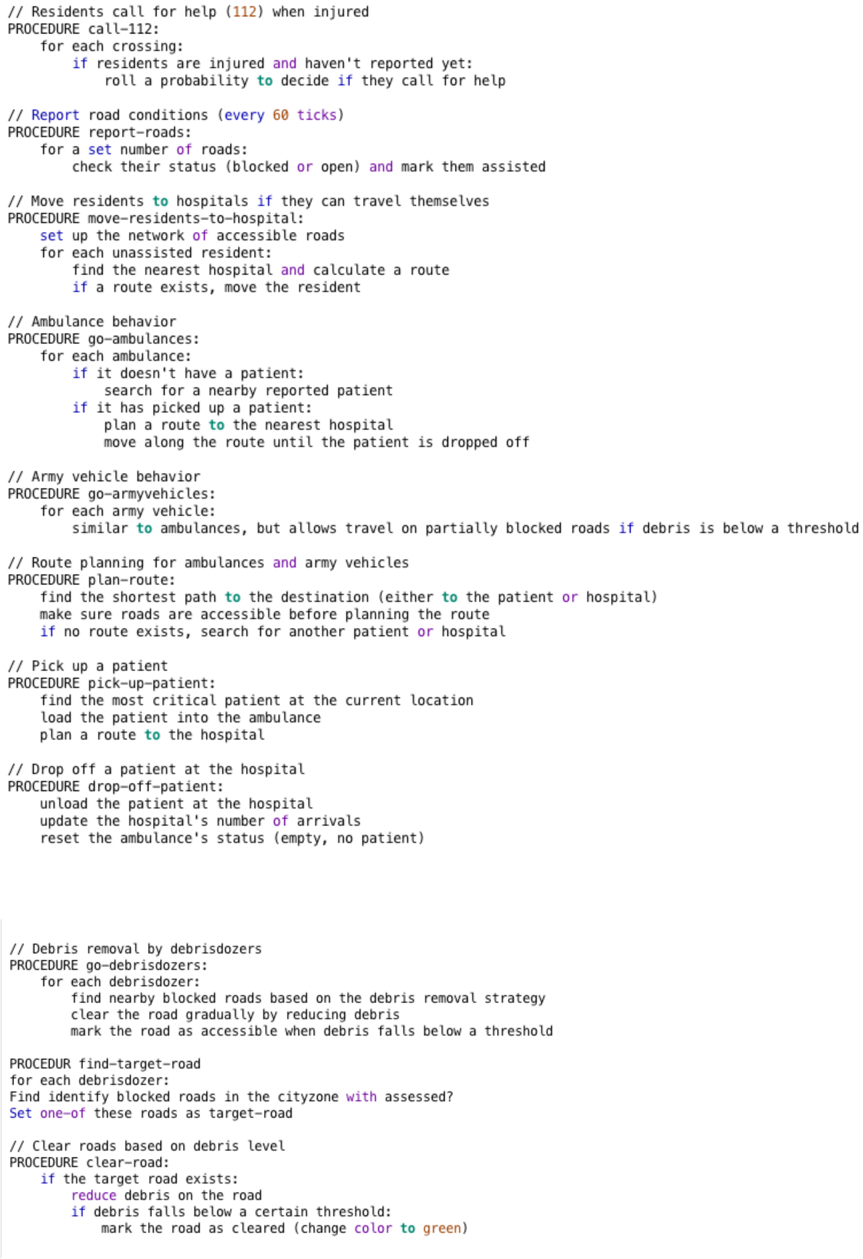
Appendix D

The Netlogo code consists out of two main parts: The ”setup” procedure and the ”Go” procedure. Within these main routines, subroutines are included. All these subroutines are focused specifically to translate certain parts of the dynamics. This appendix shows a simplified version of the code showing the logic behind the code.



```
// Load and create the road network from a CSV file
PROCEDURE create-network:
    for each row in the CSV file:
        calculate the node positions based on coordinates
        create nodes (crossings) if they don't exist yet      ; Ensures the same node is not created twice
        connect nodes with roads
        assign road lengths and IDs to each road

// Import building data from a CSV file
PROCEDURE import-buildings:
    for each row in the building CSV file:
        create buildings with the number of moderate and severe injuries
        assign coordinates and zones to each building

// Assign residents to crossings based on buildings
PROCEDURE set-residents:
    for each crossing:
        sum the moderate and severe injuries from connected buildings
        assign those values to the crossing's resident data

// Initialize hospitals
PROCEDURE init-hospitals:
    select specific crossings to become hospitals             ; Locations based on real world locations
    set hospital properties (capacity, zones, etc.)

// Block roads based on earthquake scenario
PROCEDURE block-roads:
    load blocked roads from a file
    procedure reads a different file for each seismic scenario
    Turn color or blocked roads red
    for each blocked road:
        assign a debris amount based on road length
        mark roads as unavailable for army vehicles if debris is too high

// Initialize ambulances
PROCEDURE init-ambulances:
    create a set number of ambulances
    assign each ambulance to a hospital
    set initial ambulance properties (empty, no route, patient, etc)

// Initialize army vehicles
PROCEDURE init-armyvehicles:
    create a set number of army vehicles
    assign each vehicle to a hospital
    set initial properties like ambulances, but allow them to navigate partially blocked roads
```

Figure D.1: Setup procedure



```
// Residents call for help (112) when injured
PROCEDURE call-112:
    for each crossing:
        if residents are injured and haven't reported yet:
            roll a probability to decide if they call for help

// Report road conditions (every 60 ticks)
PROCEDURE report-roads:
    for a set number of roads:
        check their status (blocked or open) and mark them assisted

// Move residents to hospitals if they can travel themselves
PROCEDURE move-residents-to-hospital:
    set up the network of accessible roads
    for each unassisted resident:
        find the nearest hospital and calculate a route
        if a route exists, move the resident

// Ambulance behavior
PROCEDURE go-ambulances:
    for each ambulance:
        if it doesn't have a patient:
            search for a nearby reported patient
        if it has picked up a patient:
            plan a route to the nearest hospital
            move along the route until the patient is dropped off

// Army vehicle behavior
PROCEDURE go-armyvehicles:
    for each army vehicle:
        similar to ambulances, but allows travel on partially blocked roads if debris is below a threshold

// Route planning for ambulances and army vehicles
PROCEDURE plan-route:
    find the shortest path to the destination (either to the patient or hospital)
    make sure roads are accessible before planning the route
    if no route exists, search for another patient or hospital

// Pick up a patient
PROCEDURE pick-up-patient:
    find the most critical patient at the current location
    load the patient into the ambulance
    plan a route to the hospital

// Drop off a patient at the hospital
PROCEDURE drop-off-patient:
    unload the patient at the hospital
    update the hospital's number of arrivals
    reset the ambulance's status (empty, no patient)
```

```
// Debris removal by debrisdozers
PROCEDURE go-debrisdozers:
    for each debrisdozer:
        find nearby blocked roads based on the debris removal strategy
        clear the road gradually by reducing debris
        mark the road as accessible when debris falls below a threshold

PROCEDUR find-target-road
for each debrisdozer:
Find identify blocked roads in the cityzone with assessed?
Set one-of these roads as target-road

// Clear roads based on debris level
PROCEDURE clear-road:
    if the target road exists:
        reduce debris on the road
        if debris falls below a certain threshold:
            mark the road as cleared (change color to green)
```

Figure D.2: Pseudocode Diagrams

E

Appendix E

E.1. Verification steps

During the model implementation many agents were checked in more detail, to check whether the translation into the model is correct. Especially when new features were added or new parts of the code were formulated, the behaviour of the specific agent was tracked by following the agent using the inspect function in Netlogo.

E.1.1. Extensive code walk-through

The model code was checked during multiple stages of development. This meant checking if the model functions were correctly translated from the conceptual model and procedures and if the code itself was correct and had the correct outcome. The main method of verification in the code was the use of 'printf() debugging' (Spence, 2020). Printf() debugging is the process of adding print statements at key points in the code in order to get more or less carefully chosen status information as output of the model. This information can be observed to deduce what is going wrong in the code.

E.1.2. Recording and tracking Agent Behaviour

This verification step was constantly performed to make sure the agents behaved the way that was expected. For example, to make sure the casualty transportation only occurs over roads that are accessible, the ambulances were constantly followed once the routing was expanded in the model. Moreover, the ambulances were followed to check if the route they planned actually goes to the right resident in the model and to check if the ambulances do indeed follow the route that they planned.

Another example occurred when implementing the debris dozer, I had to make sure they all operate in a specific zone. It was important to check whether the target-road of the debris dozer was actually located in that specific zone. Thus, the debris dozer was followed and the target-roads were checked.

Whilst implementing the army vehicles, it was very important to make sure that the thresholds set for the roads actually worked and that these vehicles actually behave differently then the ambulances. In the beginning the army vehicles used all blocked roads which is not was was intended. In order to overcome this error, a new was variable was added to the roads: ”availablefor army?”. Using this variable made it possible for the army vehicles to only use available roads and blocked roads of which the ”availableforarmy” varibale is true. After implementing this new variable the army vehicles were tracked and in can be concluded that they indeed only choose a route over green roads or red roads where the debris is less then the set threshold.

E.1.3. Other verification

In order the cityzones were translated correctly into the model, a variable was created and the observer command was used to give each zone a different color to check whether the zones were implemented correctly. As is portrayed in figure E.1 the zones are correctly translated into the model.

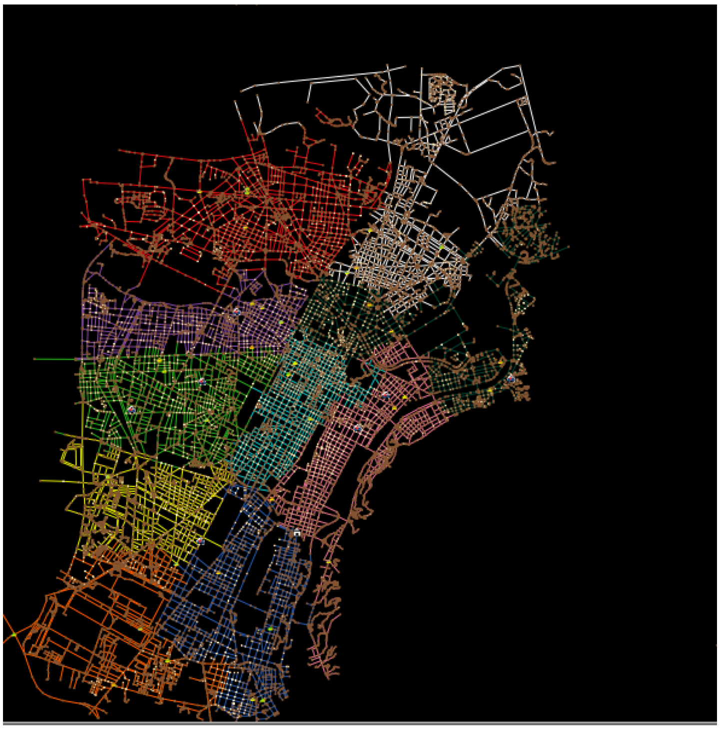


Figure E.1: Verification of cityzones

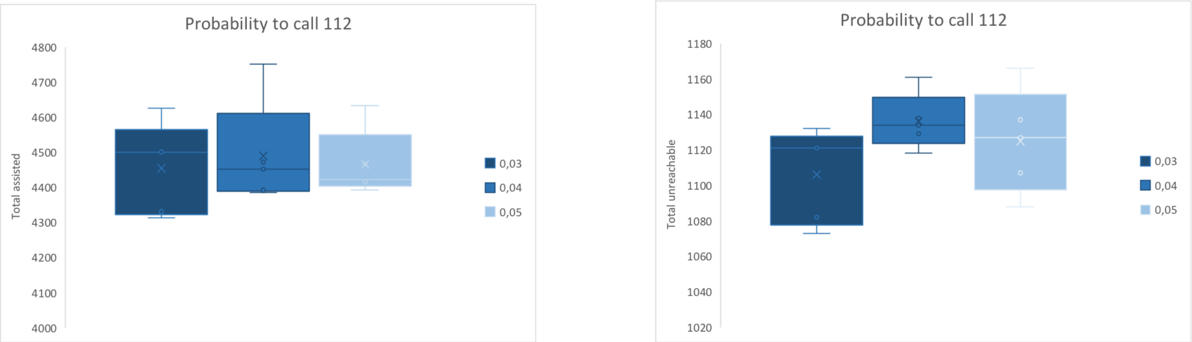
Additionally, the outcomes of the model were also verified to make sure the model calculates the outcomes in the right way. To achieve this, all indicators are summed to check whether the overarching KPI is indeed the sum of these individual indicators. This is the case so it can be concluded that the KPI's are calculated correctly in the model.

E.2. Validation

The parameters that are varied are shown in Table E.1. The sensitivity analysis is performed on the two main KPI's. This means the individual measurements for each indicator are not considered.

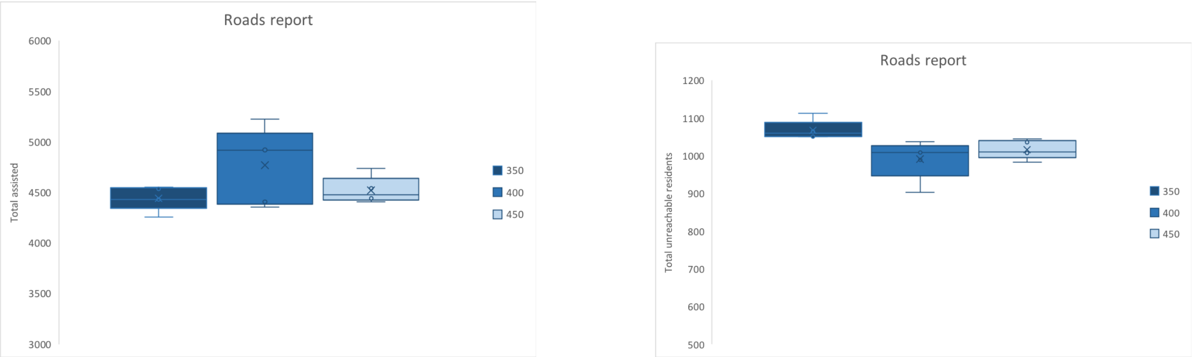
Table E.1: Parameter Settings

Parameter	**Parameter space**	**Repetitions**
Probability-to-call112	0,03;0,04;0,05	10
Number-roads-report	350;400;450	10
Number ambulances	10;25;40;55	10
Amount debris dozers	10;20;30	10
Thresholds for blocked roads	low;high	10



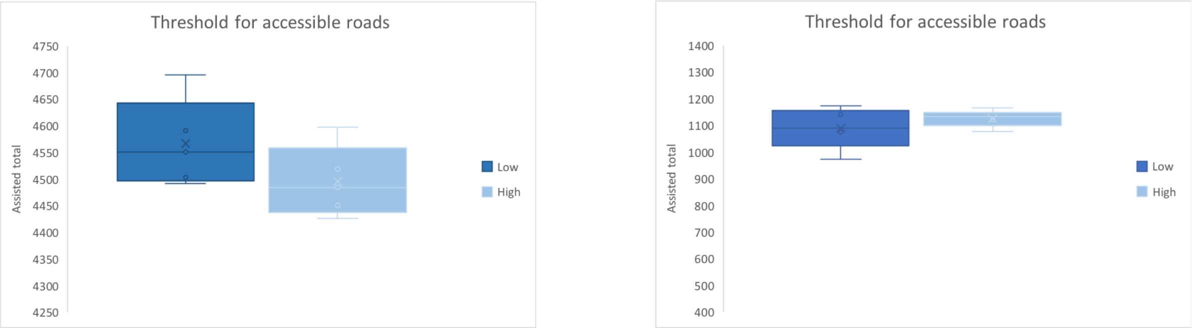
(a) **(b)**

Figure E.2: Sensitivity analysis probability to call 112



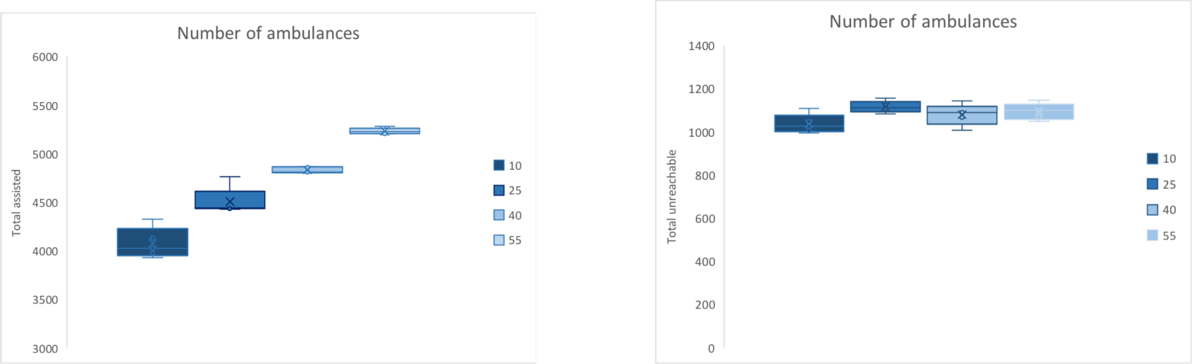
(a) **(b)**

Figure E.3: Sensitivity analysis number roads report



(a) **(b)**

Figure E.4: Sensitivity analysis threshholds for accessible roads



(a)

(b)

Figure E.5: Sensitivity analysis number of ambulances

F

Appendix F

This Appendix shows the results for the unreachable residents per zone.

Table F.1: Results of unreachable residents under the Kobe scenario

	Total	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Base case	72%	76%	70%	80%	78%	59%	63%	72%	65%	48%	57%
25A 20D											
Population Density	72%	68%	49%	66%	75%	50%	77%	82%	84%	52%	72%
Distance to Hospitals	62%	59%	79%	63%	72%	83%	75%	81%	38%	74%	76%
25A 40D											
Population Density	**50%**	33%	32%	35%	86%	33%	58%	61%	67%	37%	72%
Distance to Hospitals	**41%**	29%	63%	34%	67%	80%	93%	65%	21%	68%	80%
35A 20D											
Population Density	**73%**	68%	52%	74%	69%	76%	62%	74%	83%	81%	52%
Distance to Hospitals	63%	58%	67%	62%	73%	84%	81%	83%	50%	58%	74%
35A 40D											
Population Density	**55%**	36%	37%	38%	59%	42%	52%	64%	68%	36%	81%
Distance to Hospitals	**42%**	34%	63%	36%	66%	70%	82%	60%	19%	72%	62%

Table F.2: Results of unreachable residents under the El Centro scenario

	Total	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Base case	69%	77%	71%	78%	61%	50%	0%	61%	52%	58%	67%
25A 20D											
Population Density	**73%**	77%	51%	77%	66%	32%	0%	76%	94%	101%	68%
Distance to Hospitals	**70%**	59%	86%	64%	86%	76%	0%	102%	33%	81%	86%
25A 40D											
Population Density	**46%**	37%	30%	37%	71%	34%	0%	70%	71%	66%	96%
Distance to Hospitals	**45%**	22%	78%	34%	66%	96%	0%	76%	17%	93%	82%
35A 20D											
Population Density	74%	71%	55%	71%	81%	57%	0%	76%	78%	76%	73%
Distance to Hospitals	68%	63%	103%	54%	81%	49%	0%	98%	31%	79%	90%
35A 40D											
Population Density	**50%**	36%	32%	38%	64%	8%	0%	46%	58%	61%	66%
Distance to Hospitals	**44%**	32%	63%	32%	75%	49%	0%	60%	13%	83%	80%

G

Appendix G

This chapter shows the steps made to conclude whether the effects of the experiments are statistically significant.

First, the necessary data is gathered from the experiments. Once the data is collected, a decision is made regarding which experiments will be compared to assess whether adding a specific factor has a significant impact on the Key Performance Indicators. To evaluate the statistical significance of the differences between these experiments, t-tests are performed. These tests compare the results before and after the added intervention to determine whether the observed differences are statistically significant or merely due to randomness.

Table G.1 and tabel G.2 provide an overview of which experiments are tested against each other.

Table G.1: Comparison for t-test Kobe scenario

Experiment ID	Compared to	Difference
1	BC1	Debris removal strategy
3	BC1	Debris removal strategy
5	1	Number of dozers
7	3	Number of dozers
9	1	Number of ambulances
11	3	Number of ambulances
13	9	Number of dozers
15	11	Number of dozers

Table G.2: Comparison for t-test El Centro scenario

Experiment ID	Compared to	Difference
2	BC2	Debris removal strategy
4	BC2	Debris removal strategy
6	2	Number of dozers
8	4	Number of dozers
10	2	Number of ambulances
12	4	Number of ambulances
14	10	Number of dozers
16	12	Number of dozers

Table G.3 and G.4 display the corresponding p-values that results from the t-test performed.

Table G.3: P-values in Kobe scenario

ID	Severe	Moderate	Self-moderate	Self-severe	Total-assisted	Unreachable
1	0.05	0.14	0.05	0.05	0.18	0.94
3	0.00	0.099	0.027	0.15	0.027	0.00
5	0.66	0.073	0.15	0.23	0.18	0.00
7	0.34	0.38	0.00	0.05	0.00	0.00
9	0.00	0.11	0.17	0.05	0.00	0.87
11	0.00	0.00	0.91	0.01	0.11	0.30
13	0.00	0.3	0.05	0.12	0.10	0.00
15	0.05	0.28	0.00	0.194	0.00	0.00

Table G.4: P-values in El Centro scenario

ID	Severe	Moderate	Self-moderate	Self-severe	Total-assisted	Unreachable
2	0.00	0.89	0.83	0.48	0.81	0.05
4	0.05	0.18	0.12	0.47	0.1	0.05
6	0.86	0.76	0.23	0.05	0.2	0.00
8	0.69	0.87	0.09	0.00	0.12	0.00
10	0.00	0.00	0.32	0.00	0.03	0.75
12	0.00	0.00	0.46	0.00	0.03	0.12
14	0.00	0.64	0.16	0.05	0.17	0.00
16	0.00	0.82	0.07	0.11	0.12	0.00