MSc thesis in Engineering and Policy Analysis

Increasing situational awareness in the golden period of the response phase of sudden-onset disasters by mapping community reachability

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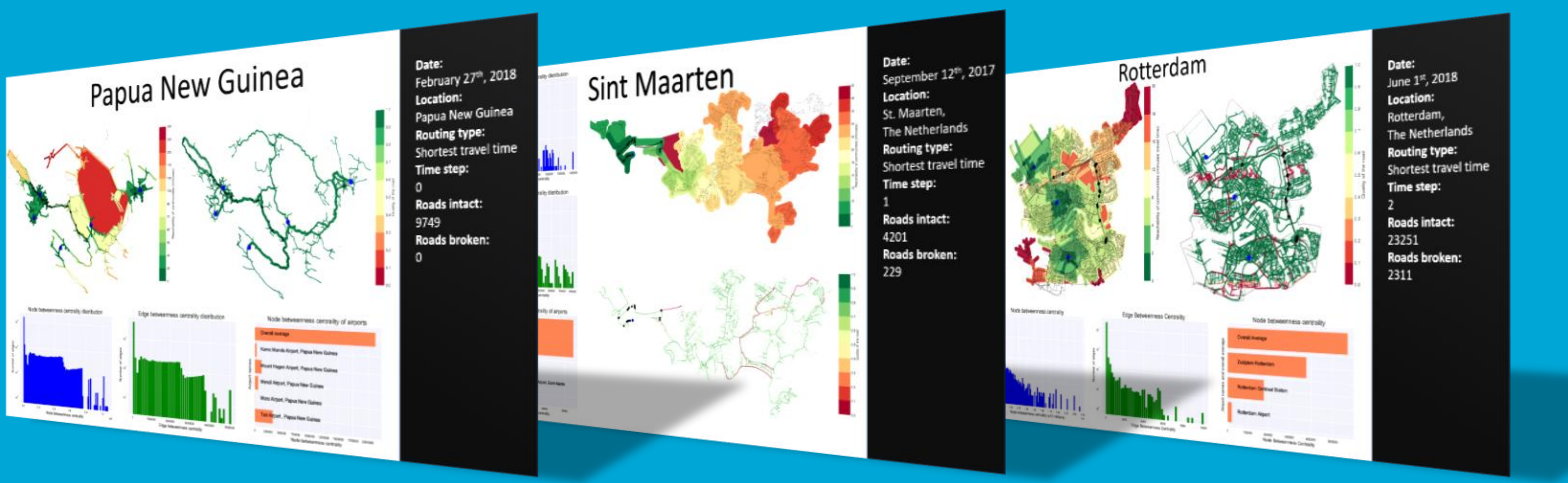

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INCREASING SITUATIONAL AWARENESS IN THE GOLDEN PERIOD OF THE RESPONSE PHASE OF SUDDEN-ONSET DISASTERS BY MAPPING COMMUNITY REACHABILITY

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

Master of Science
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by

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TU Delft

PREFACE

Please be welcome to read my Master Thesis, which is the product of my final endeavour of finishing my Master of Engineering & Policy Analysis, and therewith terminating an important chapter in my life. This thesis is inspired by all the great work that is done by humanitarians for victims of humanitarian crises. This thesis describes my research that I've been involved with, in the past six months, about designing an information system that collects information about the reachability of communities in disaster-struck areas.

Every day I have learnt a lot during this great journey that is my research. I had the opportunity to take a look inside the complex and tumultuous world of humanitarians. Thanks to the Humanitarian Aid Thesis Circle, I could get into contact with many inspiring people that helped me a lot to understand the complexities of humanitarian aid.

Now, first of all, I want to thank Martijn Warnier, who has been incredibly helpful as my first supervisor. Martijn helped me to obtain ideas, gave me great feedback and guided me in such a way that everything went according to planning. Our frequent meetings where good for my motivation to keep going and the supportive attitude of Martijn decreased my concerns.

I want to thank Bartel van de Walle as well, for his inspiring knowledge about this complex world of the humanitarians and for giving me so many opportunities to get into contact with important people from the field. You were able to motivate me to pursue this field of research by showing me the relevance of it.

Similarly, I'd like to thank Kenny Meesters for taking the time to brainstorm with me and for giving me advice when it was needed, and opening up doors that would have been closed otherwise.

Also, I want to thank Inge a lot for always being supportive, patient and for keeping me optimistic. Also, I want to thank my parents for showing interest in my research and giving me all the support they could give.

Last but not least, I want to thank my roommates with whom I could have endless talks and discussions about all of our theses at the dinner table. Special thanks go out to Tim, with whom I've interchanged many thoughts, for giving me constructive feedback along the way and having good conversations during lunches in the Wijnhaven's desert.

I hope that after reading this thesis, you'll be convinced that there is a goldmine of information openly available, that can help us to make this world a better place.

EXECUTIVE SUMMARY

The world today faces many challenges concerning sea-level rise, rising tensions between nations, natural disasters, food security, extreme droughts, and more. Due to ongoing climate change and a growing world population, the world faces stronger natural disasters affecting more people. Different NGO's and UN agencies have been active in humanitarian aid for a long time and are continuously working hard to manage the response to humanitarian disasters. When a disaster strikes, it's important for the affected communities to be reached by aid workers timely (Pacific Disaster Center, 2017; Meyer, 2017). For aid workers to live up to this, they need information on who needs to be reached, how long it takes to reach victims, and how this information changes over time. The problem that arises when a sudden-onset disaster strikes, is that it comes unexpected and therefore there isn't a lot of time to analyse the area to create an overview of the situation. Information is essential to effective disaster response, but it takes time before information comes available (Duran, Ergun, Keskinocak, & Swann, 2013).

In this research, a literature review is conducted to elaborate on the issue in the relief operations, specifically on the last-mile of humanitarian logistics. Last-mile distribution is the final stage of the humanitarian relief operations that consists of the delivery of relief supplies from local distribution centres to affected people by a disaster (Balcik, Beamon, & Smilowitz, 2008). The coordination issues that exist in relief operations are explored and one of the important issues that are described in the literature is the lack of information available to aid workers. Information is needed to create a level of situational awareness among aid workers in disaster response situations. Geographic maps have an important role to play in providing aid workers with situational awareness, however, it's yet unclear how it can be implemented in a way that will improve situational awareness and the coordination of relief efforts (Madey et al., 2007). The objective of this research is to design an information system that is able to concentrate relevant information of a road network where a disaster has occurred rapidly and therewith improving situational awareness of aid workers in the response phase of a sudden-onset disaster. The information system that is designed is a reachability model that allows decision-makers to map the road network of large areas and to visualise the reachability the area relative to the entry points used by aid workers in a disaster. The research question that is posed is as follows:

> **How can situational awareness in the golden period of the response phase of sudden-onset disasters be improved with a dynamic visual representation of the community reachability by aid workers?**

The framework of Hevner, March, Park, and Ram (2004) is used as an approach to address the research question. The environment in which the information system would be used is first explored by identifying stakeholders and requirements. Then graph theory and visualisation techniques are elaborated on to conceptualise a reachability model.

A reachability model is constructed and implemented by using OpenStreetMap data to reproduce road networks of a specified area. the model is constructed as such, that a user has to insert a location for which the model should generate a road network, and insert entry points from where relief operations will be planned. The model is configured to accept changing data of road conditions and entry points. The reachability model allows creating a geographic map of any region that shows the reachability of different segments of the area with a certain colour. The reachability can be measured in minutes travel time, distance in meters or a combination of travel time and road capacity. The model also creates a visualisation of the road qualities and meta-information of the road network's characteristics. These visualisations are combined into a dashboard that makes interpretation easier. This dashboard can be created rapidly, relative to other assessments of disasters.

The feasibility of the designed reachability model is evaluated by conducting two case-study experiments and expert interviews. The case-studies are conducted for Sint Maarten and Papua New Guinea, reconstructing the disasters of hurricane Irma and the 2018 earthquake of Papua New Guinea. The case-studies demonstrate that the reachability model can give additional insights for aid workers when the visualisations are combined with humanitarian parameters of other impact assessments of the disaster area, demonstrating the usefulness of the model in reality. Also, the reachability model can be configured very rapidly and changed easily, which is helpful for aid workers, because time is essential to effective disaster management and the disaster situation is constantly changing Duran et al. (2013). The positive evaluation is confirmed in the interview conducted with two experts that have been involved in the disaster response on Sint Maarten after hurricane Irma. The model is considered especially helpful for prioritising response activities, determining locations for shelters and medical facilities, and reaching and transporting critical patients as efficiently as possible. However, the most important perk of the reachability model is that it allows aid workers to create a preliminary assessment very rapidly in the golden period of the response operations, which is a unique feature of this model.

The model limitations that are identified in this research are the lack of including traffic congestion in determining reachability by travel time. Furthermore, communities that are not directly adjacent to a road, like often in Papua New Guinea, currently cannot be included in the reachability model. Also, the lack of a validation to what extent the reachability model represents reality is something that needs to be considered in future research.

How can situational awareness in the response phase of a sudden-onset disaster be improved with a dynamic visual representation of the community reachability by aid workers? The situational awareness can be improved by using a reachability model as designed in this research that's rapidly deployable and easily adjustable when new information becomes available and visualising the outcomes of the model on a geographic map. Situational awareness can be improved to the extent that combining the reachability model's outcomes with humanitarian parameters can give additional insights that may help aid workers with prioritising aid, placing shelters or medical facilities and knowing how long it takes to deliver aid to people in need.

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1 INTRODUCTION

> "All across the world, ...increasingly dangerous weather patterns and devastating storms are abruptly putting an end to the long-running debate over whether or not climate change is real. Not only is it real, it's here, and its effects are giving rise to a frighteningly new global phenomenon: the man-made natural disaster."
>
> *Barrack Obama*

1.1 BACKGROUND

The world today faces many challenges concerning sea-level rise, rising tensions between nations, natural disasters, food security, extreme droughts and more. September 2017 reminded the international society that natural phenomena such as the devastating hurricanes Harvey, Irma, Jose and Maria can result in unexpected sudden-onset humanitarian crises with terrible consequences (Astor, 2017). Also, earthquakes such as in Hela Province in Papua New Guinea in February 2018 also occur occasionally resulting in casualties and injured people (ABC News, 2018). Due to the ongoing climate change, hurricanes will become stronger and more dangerous while creating more destruction in the years to come (Meyer, 2017). As the sea-level rises, certain populations will become more vulnerable to floods, tsunamis or hurricanes. These threats to humanity - either man-made disasters like wars or natural disasters - evidently ask for more effective humanitarian aid when a disaster strikes. Where a disaster is defined as a "serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" (Cinnamon, Jones, & Adger, 2016, p. 254). Different NGO's and UN agencies have been active in humanitarian aid for a long time and they are facing more challenges, as the world will encounter more humanitarian crises. Exposure and vulnerability of people play a large role in humanitarian disasters. If an enormous tsunami sweeps over an uninhabited island, it wouldn't be considered a natural disaster if there are no human victims. The population of the world is increasing and with the sea-level rising, there is a tendency for more people to become exposed to potential disasters (Cutter et al., 2008). With the knowledge that more disaster will happen in the following years, it has become more and more relevant to manage disasters adequately and effectively. Disaster management consists of four sequential phases, mitigation, preparedness, response and rehabilitation (Van Wassenhove, 2006). Mitigation is the phase where risk-reducing measures are taken in case a disaster strikes. Preparedness is the phase where people know what to do as soon when a disaster occurs. The response is the phase where a disaster has taken place and actions need to be undertaken to help victims of a disaster in order to reduce the fatality rate as much as possible. Rehabilitation consists of the recovery of a community and reconstructing society (Van Wassenhove, 2006). This research is focusing on the response phase of sudden-onset disasters and the execution of the last mile of relief distribution. A sudden-onset disaster strikes unexpectedly with no warning, making a timely response difficult (Duran et al., 2013). The response phase is the phase directly after a disaster strikes where actions are focused on providing medical support to casualties and limiting the impacts a disaster has on a community (Duran et al., 2013).

1.2 PROBLEM STATEMENT

In the aftermath of a natural disaster, entry points such as airports and harbours play an important role in supporting emergency response activities. Airports often serve as important logistical hubs, connecting the communities affected by a sudden-onset disaster with relief supplies and support from humanitarian organizations (Van De Walle, 2018; Economist Intelligence Unit, 2005). Airports also serve as a coordination and information centre, where multiple humanitarian organizations are located and coordinate their rescue teams from. Furthermore, both airports and harbours are locations from where inbound relief organisations can find access to the area that is struck by an area. In a disaster, communities may become reliant on a nearby airport or harbour for receiving aid. An entry point could become critical for victims during a sudden-onset disaster, meaning that the functioning of the airport or harbour is of vital importance for the survival of the affected communities. A critical entry point is defined as an entry point whose destruction could change the whole network where it's connected to in terms of connectedness. This means that if a critical entry point gets damaged in a disaster, the lifeline for the victimized community gets endangered (Demšar, Špatenková, & Virrantaus, 2008). A destruction of a critical entry point could result in more casualties during a disaster.

Some people live in very remote areas, relative to entry points from where relief organisations would find access to the area. Remote in the sense of a large distance, but also in the sense of reachability as a result of road conditions or quality of other infrastructures. Meaning that if a disaster would occur, victims in remote areas might be difficult to reach by aid. An example of problems with reachability could be seen during the Nepal earthquake of 2015, where victims in remote villages were difficult to reach by foreign aid (Kazmin, 2015), because in some cases aid had to be delivered on foot, as roads were damaged or absent (Chan, 2015). For affected communities, it's important that they are able to be reached by aid workers. Aid workers need to know who needs to be reached, how long this takes, and how this information changes over time. However, a sudden-onset disaster comes unexpected and therefore there isn't a lot of time to analyse the area to create an overview of the situation, while time is a critical measure of the effectiveness of humanitarian response (Duran et al., 2013). Information is essential to effective disaster response, but it takes time for information to flow in and it needs to be managed properly. This information helps to create situational awareness among aid workers, which is needed for effective disaster management (Huyck, Verrucci, & Bevington, 2014). Aid workers often make use of transport to reach and to deliver relief for victims of a sudden-onset disaster, while the pace of humanitarian aid is highly dependent on the logistic relief operations (Thomas, 2003). The planning of their operations therefore partly consists of logistics. For making decisions based on the logistics towards victims, information about the road network is required for priority and planning purposes.

This research focuses on the lack of information about a road network in the golden period of the response phase of a disaster. The golden period is a metaphor for the crucial first moments right after a disaster has occurred. The golden period is a period where initially there is no information or situational awareness available. In this research, an information system is designed that is able to concentrate relevant information of a road network where a disaster has occurred rapidly and therewith offering a solution to the issue by improving situational awareness in the golden period of the response phase of a sudden-onset disaster.

1.3 RESEARCH OBJECTIVE

This research aims to develop a model that allows decision-makers to explore regions and the reachability of parts of a region in the golden period of the response phase, taking intrinsic system properties into consideration. This model will then allow decision-makers to map large areas and visualise the level of connectedness with an airport or harbour of all locations in a region. This model will help aid workers by providing them with essential information to support their decisions, such as how long it takes to travel to certain affected areas, or how important some aspects of the road network are. The model should change as quickly as possible after the road network's characteristics change, this way aid workers will always be up to date about the developments of the disaster situation. The objective of this research is to create a model that improves situational awareness in sudden-onset disasters. Currently, many comprehensive assessments are presented on geographic maps already, but creating these maps often takes a long time. Before these can be created, valuable time passes where situational awareness is crucial for effective relief operations. This research aims to fill the information gap between the moment a disaster occurs and the moment more comprehensive assessments are created. This period is referred to as the golden period in this research. In Figure 1.1, the aimed value of the model of this research is compared with other assessments that are created in the post-disaster phase. This figure shows that the reachability model of this research has a high value in the golden period of the disaster response phase until a certain amount of time has passed when other (sometimes more comprehensive) assessments are made. Examples of other assessments in the disaster response phase can be found in Appendix I.

It will be evaluated whether a reachability model has the potential to improve situational awareness in sudden-onset disasters and what type of decisions could be supported by a reachability model. The outcomes of this research will shed light on the potential of reachability models in disasters.

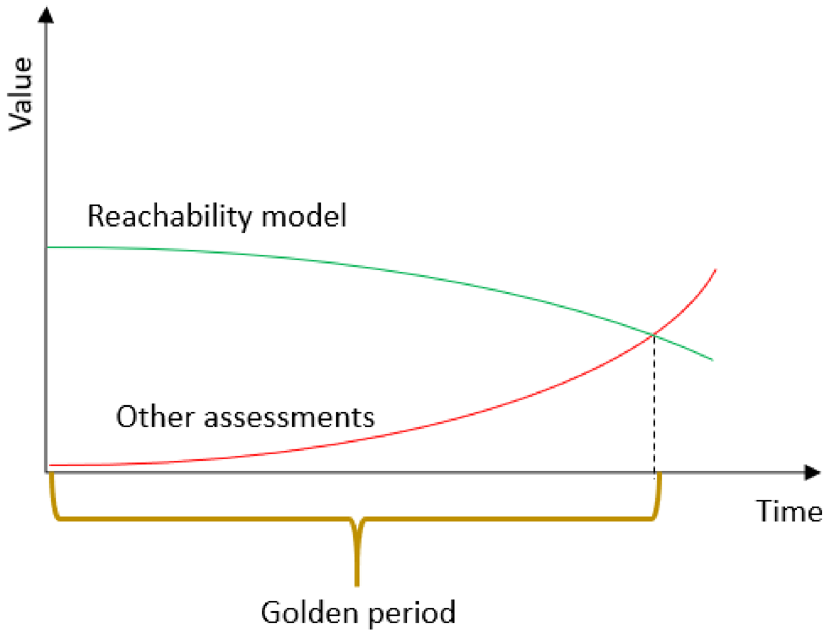

Figure 1.1: Conceptual representation of the value of the reachability model of this research compared to the value of other assessments in the disaster response phase over time. As time passes, other assessments become more valuable as they are often more comprehensive. The golden period is the time where there isn't a lot of information available.

To fully understand humanitarian logistics in the response phase, a literature review is conducted, to explore this field and to understand the scientific needs. A knowledge gap will be identified that shapes the direction of the research that leads to research questions that are to be answered throughout the research with several methods. The approach of addressing the knowledge gap and the research questions is the design approach of Hevner et al. (2004). While following this approach, the reachability model is conceptualised by exploring what is required in a model and pairing this with what tools and knowledge are available. Once the model design is conceptualised, the construction and implementation of the model are conducted to be followed by creating visualisations that display reachability in areas. Once the reachability model is set up, the model is evaluated by conducting two case-studies on disasters in Sint Maarten and Papua New Guinea. The case-study outcomes are afterwards evaluated by field experts of the disaster on Sint Maarten. The outcomes of the evaluation are then discussed and the conclusions of this research can be drawn.

1.4 RESEARCH SCOPE

According to Van Wassenhove (2006), there are 4 categories of disasters, either sudden-onset or slow-onset, and either natural or man-made as illustrated in Figure 1.2. In this research, a reachability model is created that analysed the last mile of humanitarian logistics for the response on a natural sudden-onset disaster. The reason why the focus is on natural sudden-onset disasters is that in this category there is a high necessity for information and

	Natural	Man-made
Sudden-onset	Earthquake Hurricane Tornadoes	Terrorist Attack Coup d'Etat Chemical leak
Slow-onset	Famine Drought Poverty	Political Crisis Refugee Crisis

Figure 1.2: Phases of disaster management (Van Wassenhove, 2006, p. 476)

a lot of uncertainty. At the same time, there aren't many conflicting objectives as in man-made disasters. Therefore natural sudden-onset disasters are focused on in this research. In this research, a reachability model is created to analyse the last mile of humanitarian logistics in the response phase of a natural sudden-onset disaster. To calculate the reachability, road quality, travel speed, road capacity, and locations of entry points to a country are included. Other factors that may influence reachability are neglected. Centrality measures are used to determine the importance of certain network segments in the model. To determine reachability, only transport by land vehicles on roads is included. This information is used to improve situational awareness in disaster response, but quantitative measurements of the effect the model has on situational awareness are not included.

2 LITERATURE REVIEW ON LAST-MILE OF HUMANITARIAN LOGISTICS

"What you know, you know, what you don't know, you don't know. This is true wisdom"

Confucius

This chapter consists of a literature review that explores previous research on the last-mile of aid delivery and the situational awareness of aid workers during the response phase of sudden-onset disasters. The aim of this literature review is to explore these fields of research and identify a knowledge gap that combines these fields of research, shaping the direction of this research.

"Last mile distribution is the final stage of a humanitarian relief chain; it refers to delivery of relief supplies from local distribution centres (LDCs) to beneficiaries affected by disasters." (Balcik et al., 2008, p.1). The last-mile of aid delivery is of high importance in disaster response and airports serve a great role in providing assistance to the last-mile of aid delivery. Efficient organisation of humanitarian logistics is still an unresolved matter, as the main worry for humanitarian organisations has been the raising of funds for a very long time (Chandes & Paché, 2010). Since quite recently, research on the topic of humanitarian logistics and the last-mile distribution of emergency supplies is emerging and several approaches to maximize the efficient use of resources during the response on a disaster have been developed over the past decade. There are several important topics in the last-mile of humanitarian logistics during the response phase of sudden-onset disasters. First of all, the coordination of relief efforts during a sudden-onset disaster often raises a lot of problems, while it is of vital importance for an effective disaster response (Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010). One of the issues that obstruct effective coordination of relief efforts is a lack of situational awareness. Situational awareness helps relief organisations to make the right decisions on the right moment (Huyck et al., 2014). Furthermore, a high level of disaster preparedness leads to a better performance of relief operations in the last-mile of humanitarian logistics (Brevery, 2015). However, there are many constraints on disaster preparedness that make it difficult for countries or relief organisations to be appropriately prepared. Besides constraints on disaster preparedness, there are more challenges in the last-mile of humanitarian logistics that deserve attention. This literature review focuses on these topics and explores how vulnerability mapping of communities supports disaster management according to research, and how it may be used to improve situational awareness.

2.1 COORDINATION ISSUES

There is an increasing number of stakeholders involved in emergency aid, which often leads to issues in the coordination of all these stakeholders. While only with a collective strategy of all involved stakeholders will the performance of humanitarian logistics improve (Chandes & Paché, 2010). Coordination describes "the relationships and interactions among different actors operating within the relief environment" (Balcik et al., 2010, p.23). Over the past decades, there have been many developments in improving the coordination in humanitarian aid. This is proved by the existence of bodies such as the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA), the Emergency Response Coordination Centre (ERCC) of the EU and more. However, there are still many challenges facing effective coordination in humanitarian relief, because there is no single individual or group that really controls a relief operation (Balcik et al., 2010). Usually, the government of an affected country is responsible for relief operations, but governments often lack experience and knowledge of disaster management and governments could be overwhelmed by the impact of a disaster, leading to insufficient disaster management.

Van Wassenhove (2006) proposes that private sector logistics should be applied to humanitarian logistics in order to improve its performance. Humanitarian logistics has specific characteristics that make operations management difficult, but are also similar to those of lean management in the private sector; it has an acute time frame, it is connected to a disaster at a certain point in time, there is a need for intervention teams that are not used to working together and it has the ability to put multiple resources rapidly to use and coordinate them (Chandes & Paché, 2010).

According to Balcik et al. (2010) there are several factors that affect effective coordination in humanitarian relief. The number and the diversity of actors involved in disaster response is one important factor. Even though most actors have a similar objective, there is a score of different primary motives, missions and operating constraints, but also differences in geographical, cultural and organisational policies that could create issues in effective coordination. Another important factor that affects effective coordination in humanitarian relief, is the reliance of relief organisations on donors. Relief organisations can't initiate relief operations in a country until donations have come available. This negatively impacts coordination among relief organisations. Also, a factor that impacts effective coordination is the competition for funding among relief organisations. Relief organisations could withhold information from others in order to keep a competitive advantage in attracting donors, while transparency is paramount to effective coordination (Balcik et al., 2010). The unpredictability of sudden-onset disasters is a key factor that affects coordination as well. Unpredictable characteristics are the location, time and intensity of a disaster, but also the society's characteristics, such as the characteristics of an affected population, the transportation network and other infrastructures are unknown in advance. After a sudden-onset disaster, these society's characteristics are mostly not readily available, similarly information about the post-disaster infrastructure damage, making it complicated to coordinate relief organisations appropriately. The lack of available information leads to a low situational awareness (Balcik et al., 2010). Moreover, uncertainties and lack of information among other reasons, often lead to resource scarcity or oversupply. In situations of resource scarcity, relief organisations may compete with other organisations for the same resources, which has a negative impact on coordination efforts (Balcik et al., 2010). The last factor that affects coordination efforts on relief organisations are the costs associated with coordination. As many organisations have scarce resources and are reliant on donors, there may not be time or people available to participate in coordination meetings that are essential to an effective coordination initiative (Balcik et al., 2010).

The above describes all kinds of issues that affect the coordination of relief operations in the response phase of a sudden-onset disaster. It is yet unclear how the coordination of relief operations should be coordinated and how the lack of information and resources should be handled.

2.2 SITUATIONAL AWARENESS

Situational awareness is a term used in aviation that is defined as *'the perception of the elements in the environment within a volume of time and space, comprehension of their meaning and the projection of their status in the near future'* (Endsley, 1988, p.97). In this research, this term is used in the context of sudden-onset disasters. Huyck et al. (2014) argue that as post-disaster response commences, an urgent need for a detailed representation of the disaster situation emerges. Situational awareness during the disaster response phase is important for effective disaster management, as the available information will guide the aid workers in their relief operations. Obtaining geographic situational awareness and sharing it across the network of stakeholders involved in the response is a critical success factor in the first moments after the sudden-onset disaster event (Harrald, 2006). The first moments after a sudden-onset disaster event will further be referred to as the golden period. Situational awareness in a sudden-onset disaster is related to the available interpretable information about elements in a disaster-struck area and how this information changes over time. A common problem in disaster management is the lack of situational awareness from sources such as news reports, geographic maps, information about aid worker operations, and records of events and activities (Tomaszewski, 2011). However, Madey et al. (2007) argue that even though there is a great need for reports from on-scene coordinators, first responders, public safety officials, the news media, and the affected population, these reports often seem to be inaccurate, conflicting with other reports and incomplete in terms of geographical and temporal details. According to Tomaszewski (2011), geographic maps can play a very important role in providing situational awareness to humans in disaster management in terms of providing reports including geographical and temporal details. The use of geographical maps could support informed decision making in the response phase of a sudden-onset disaster by improving situational awareness. Huang and Xiao (2015) argue that social media data could be used to obtain geographic situational awareness in disaster response situations, but that this type of data should be combined with other tools that enhance situational awareness to reduce a bias in information. This indicates a need for more intensive use of available data to increase situational awareness during the response of sudden-onset disasters.

There is a lack of knowledge about how geographic maps could be prepared in a way that they'll support situational awareness in sudden-onset disasters, without any knowledge about the disaster upfront. It's also unknown what effect such geographical maps could have on the unpredictability of a disaster situation and the impacts of a disaster.

2.3 CONSTRAINTS ON DISASTER PREPAREDNESS

As mentioned, an issue for humanitarian organisations in the disaster management process is the reliance on donors and the current financial arrangement of humanitarian organisations. Humanitarian organisations are mostly reliant on funding from donors, and often donations come right as a disaster occurs because it is the disaster itself that attracts media attention and donations (Kovács & Tatham, 2009). As a consequence of this arrangement, there is a large constraint on the preparation for disasters by humanitarian organisations. As a consequence of this constraint, large humanitarian organisations turn to their supply network for resources, forming partnerships with private organisations (Kovács & Tatham, 2009). It's necessary to emphasize the importance of the issue that the lack of financial resources for humanitarian organisations to improve disaster preparedness leads to greater costs in the response phase when a disaster actually has taken place.

Chandes and Paché (2010) argue that an important part of disaster preparedness in terms of humanitarian logistics, is the pro-active pre-positioning of logistical resources. The location of pre-positioned resources is very important for a positive impact on the implementation of humanitarian aid during a disaster (Hale & Moberg, 2005). Kovács and Tatham (2009) also emphasize the need for disaster preparedness by, among others, pre-positioning logistical resources in regional hubs. The pre-positioning of supplies could be helpful especially for victims of a disaster that are hard to reach by humanitarian aid workers, this will give people access to goods that they would otherwise not, or only partially receive. In a case-study of the Pisco earthquake in Peru, Chandes and Paché (2010) mention that people in isolated regions received only partial support while some other areas that were easier to reach received duplicated support. However, duplicated support for some victims and partial support for other victims that are more isolated could be avoided by increasing the overall situational awareness, during the preparation phase, but also in the response phase. It is clear that disaster preparedness is very important for an effective disaster response, but there are many constraints that block a sufficient disaster preparedness. Therefore it is very important to focus on improving situational awareness during the response phase in a disaster by using information systems that help create a higher level of situational awareness.

There is a lack of knowledge about how relief organisations' reliance on financial resources for the improvement of disaster preparedness can be bypassed in order to become situationally aware in the disaster response phase. There is a need for an information system that is ready to be deployed as soon as a disaster occurs while increasing situational awareness without being resource dependent.

2.4 CHALLENGES IN LAST-MILE OF HUMANITARIAN LOGISTICS

The most important issues of the last-mile of humanitarian logistics that have been mentioned so far are coordination issues of all organisations. There is a need for management of all involved organisations to ensure an efficient approach by developing and deploying a collective strategy. Furthermore, there are donor issues with humanitarian organisations that lead to a constraint on the implementation of disaster preparedness, while the disaster preparedness in terms of efficiency is a very important aspect of disaster management, because preparedness is less expensive than mitigating damages in response to a disaster. There is a strong emphasis on the pre-positioning of emergency supplies in literature. There are various ways to identify relevant locations for supplies. Also, Chandes and Paché (2010) argue that there is a lack of the use of information systems in humanitarian operations. This is consistent with the argument of Balcik et al. (2010), where the unpredictability of sudden-onset disaster is mentioned as a key factor that affects effective coordination of relief organisations. There is a need for the deployment of information systems that can help to mitigate the consequences of this unpredictability. As a sudden-onset disaster occurs, information about the affected population, the condition of the transportation network, and the availability of airports are needed as quickly as possible. Information systems can be deployed that could make this information directly available to relief organisations as they commence the response operations. This could have a positive effect on the coordination of the relief efforts during the response phase.

One of the recommendations of Economist Intelligence Unit (2005) is to obtain a clear view of the required emergency aid delivery operations. Information systems can be used to get this clear view of where there could be people in dire need of relief, but are hard to reach or vulnerable to disruptions in the network when a disaster strikes. There is plenty of research that develops multi-criteria optimisations to optimise the distribution of relief supplies in the last-mile (Ferrer et al., 2012; Vitoriano, Ortuño, Tirado, & Montero, 2011; Chang, Wu, Lee, & Shen, 2014; de la Torre, Dolinskaya, & Smilowitz, 2012; Van Hentenryck, Bent, & Coffrin, 2010). However, this research does not consider how vulnerable some communities are in terms of connectivity with aid from humanitarian organisations and how this is a consequence of the condition of the road network. Brevery (2015) concludes that for relief operations to work well and be well-coordinated, updated and real-time information is necessary. Complex network analysis can be useful to obtain information about potentially isolated areas, reducing the risk of situations like during the Pisco earthquake in Peru, where isolated areas did not get enough support from relief operations because there was no clear coordination (Chandes & Paché, 2010).

Information systems can be used in the response phase of sudden-onset disasters to support aid delivery operations in a disaster-struck area. It can help to analyse where people might be hard to reach and to reduce the risk of people becoming isolated from aid. An information system requires recent and dynamic information to support relief operations. There is currently a lack of knowledge about how such an information system should be, in order for it to support relief operations.

2.5 MAPPING VULNERABILITY OF COMMUNITIES

"Vulnerability is the key to an understanding of risk" (Bankoff, Frerks, & Hilhorst, 2013, p.4) and looking at disasters by examining vulnerability can offer good insights, especially in a time where natural disaster are becoming more frequent (Bankoff et al., 2013). The vulnerability is a way to measure the exposure to the risk from natural disasters very precisely. It's considered a more accurate measure than poverty, because not all poor people are vulnerable to disaster, just like not all people that are vulnerable to disasters are poor (Bankoff et al., 2013). The vulnerability itself is very difficult to measure because it is multi-dimensional and driven by many factors (Wagner & Bode, 2006; Cardona et al., 2012). It is argued by Cardona et al. (2012), that a lack of connectivity in a road network is a driving factor for the vulnerability and disaster risk of communities. Therefore, in this research, the reachability of people through a road network is considered as a driving factor for vulnerability, and is used to quantify the vulnerability of communities to the aftermath of sudden-onset disasters.

A good way to examine reachability is to create geographic reachability maps, giving a clear insight into the vulnerability of communities during sudden-onset disasters. "It is widely acknowledged that maps are essential in the earliest stages of search and rescue, that evacuation planning is important, and that overhead images provide the best early source of information on damage" (National Research Council, 2007, p.2). Morrow (1999) explains that mapping the areas where many high-risk households live, could help to improve the mitigation efforts to address this vulnerability and supports an adequate response during disasters. Research of Cova and Church (1997) explores how evacuation assessment can be performed when the population to evacuate is unknown. It introduces a method that allows researchers to focus on the spatial variation in evacuation difficulty across a landscape. It's a systematic geographic approach to examine community evacuation vulnerability including the production of geographic maps to visualise these vulnerabilities. These maps are suitable to complement other hazard maps. The research of Cova and Church (1997) mainly focuses on the evacuation part of a natural disaster, and the vulnerability is defined by the number of evacuees per lane of an escape route. It doesn't include the accessibility of the area by humanitarian organisations with relief supplies.

Geographic visualisation techniques have been developing rapidly over the previous decades and continue to drive vulnerability mapping applications (Preston, Yuen, & Westaway, 2011). It offers effective tools for creating insights about the vulnerability in disaster-prone areas. The Index for Risk Management (INFORM) model is a proactive crisis and disaster management framework and supports the allocation of resources for disaster management and it also supports coordination of the anticipation, mitigation and preparation for humanitarian emergencies (de Groeve, Poljansek, & Vernaccini, 2015). The Index for Risk Management is a collaboration of the Inter-Agency Standing Committee (IASC) and the European Commission. "The INFORM model is based on risk concepts published in scientific Literature and envisages three dimensions of risk: Hazards & Exposure, Vulnerability and Lack of Coping Capacity. The INFORM model is split into different levels to provide a quick overview of the underlying factors leading to humanitarian risk and builds up the picture of risk by 53 core indicators" (de Groeve et al., 2015, p.2). The INFORM model creates this overview of humanitarian risk with a geographic map showing a composite indicator of this risk for municipalities, regions, provinces, and countries.

Although the INFORM model includes many factors to define vulnerability, what is not included, is the connectivity of communities with (international) aid and relating this connectivity to their vulnerability. This is both related to the remoteness of their habitation as the robustness of the infrastructure that connects them to international aid, that comes in via an airport somewhere in the country, struck by a natural disaster. Wilbrink (2017) uses remoteness as a proxy for vulnerability. Where remoteness is defined by the distance to local facilities, geographic properties of the landscape and the density figures of the population and roads. This complements the INFORM model on part of the limitations just mentioned. However, it does not research how the connectivity of (possibly remote) communities with (international) aid. This also has to do with the criticality of the connecting airport that serves as a humanitarian hub, the robustness of the road network connecting the airport to the victims and the travel time for aid workers from a humanitarian hub to a certain community.

From this paragraph, it can be concluded that mapping the vulnerability of communities is important to measure the risk for sudden-onset disasters. Maps provide necessary information in the disaster response phase and are currently used frequently by aid workers. However, there are currently no geographic maps that include the reachability of communities as a factor that drives disaster vulnerability. There is a lack of knowledge in the literature about reachability maps in a humanitarian disaster context and how this can improve situational awareness for aid workers.

2.6 KNOWLEDGE GAP

This literature review discusses literature on the last-mile of humanitarian logistics, exploring coordination issues in humanitarian logistics, the importance of situational awareness in disaster response, constraints on disaster preparedness of relief organisations and an overview of the challenges that arise associated with the last-mile of humanitarian logistics. In the literature, it's discussed that one of the most important issues of humanitarian logistics is the coordination of all involved relief organisations. There is often a lack of collective strategy and a lack of information about the unpredictable societal characteristics of a sudden-onset disaster. Societal characteristics of a sudden-onset disaster such as information of the transportation network, potential damages to this network and information about the affected population, are unpredictable and this unpredictability could be reduced by the deployment of information systems. According to the literature, this could prove positive for the coordination of emergency relief and help to improve the effectiveness of the response on a sudden-onset disaster by relief organisations. Situational awareness is paramount to effective disaster management and using information systems to improve situational awareness could lead to a more effective response.

Furthermore, it's discussed how the connectivity of communities with a road network is related to their vulnerability for sudden-onset disasters and that it is important to be able to communicate this vulnerability to aid workers to improve disaster management. The communication of vulnerability is of key importance to an understanding of risk. Proposed as a way to examine the vulnerability of communities, is to create geographic maps that expose the reachability of communities. Providing geographical maps supports an adequate response to disasters, but also supports the preparedness for a disaster. Visual representations of geographical areas should illustrate the importance of airports that serve as a humanitarian hub in an area, the robustness of the road network and the travel time for aid workers to travel from a humanitarian hub to a certain community. Until yet, there is no research that shows how geographical maps with information on reachability of communities can support coordination of relief organizations and situational awareness in disaster management.

There is a lack of knowledge about how the mapping of community reachability by aid workers could support situational awareness and coordination of relief organisations in disaster management. This research will focus on creating an artefact that allows decision-makers to map community reachability by aid workers and thus to explore how this artefact can help to improve the situational awareness during disaster response and how this may improve the coordination of relief organisations.

3 RESEARCH FORMULATION

> "The whole of science is nothing more than a refinement of everyday thinking."
>
> *Albert Einstein*

3.1 RESEARCH QUESTIONS & APPROACH

The knowledge gap identified in the previous section shows that there is currently insufficient knowledge about how the mapping of community reachability by aid workers could support situational awareness in disaster management. This research revolves around one main research question that addresses the knowledge gap identified in the previous chapter:

> **How can situational awareness in the golden period of the response phase of sudden-onset disasters be improved with a dynamic visual representation of the community reachability by aid workers?**

3.1.1 Design approach

To address the main research question, an artefact is developed that consists of the steps needed to visualise the reachability of communities vulnerable to natural disasters. The proposed research will follow the design approach of Hevner et al. (2004). The design approach consists of three elements: the Environment, the Information System Research and the Knowledge Base. A conceptual overview of the framework is illustrated in Figure 3.1. The Environment is the context of the problem, which consists in this case of the infrastructural network in a disaster-struck area, the topology of communities and the airports that are used for aid distribution. The Information System Research refers to the artefact that will define the reachability and visualise these attributes on a geographic map. The artefact is in this research a reachability model of a disaster-struck area that analyses the reachability of communities by aid workers. The Knowledge Base consists of theories, frameworks and methodologies.

The Environment has organisational needs based on the defined problem, and an artefact is designed to meet this needs creating relevance, which is known as the Relevance Cycle. The Information System Research consists of an iterative build-and-evaluate loop creating and evaluating artefacts. The Knowledge Base provides theories, frameworks and methodologies for the artefact design, while the application of artefacts to the environment create additions to the Knowledge Base. This is known as the Rigour Cycle.

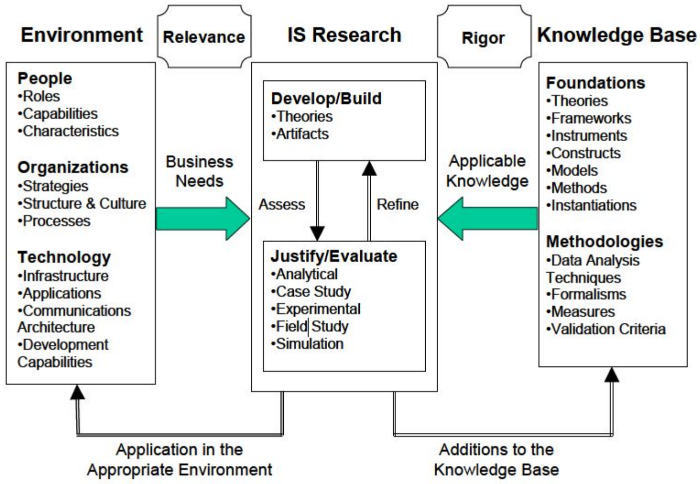

Figure 3.1: Information Systems Research Framework (Hevner, March, Park, & Ram, 2004)

3.1.2 Sub-research questions

The sub-research questions as presented in this paragraph will logically lead to answering the main research question. The sub-research questions will shape the sequence of the various processes in this research. The sub-research questions are the following:

1. What are the requirements for modelling the network of communities and their reachability?
2. How can the reachability of communities be determined and identified?
3. How can the reachability of communities be visualised?
4. How can the reachability model support decision-makers to improve situational awareness in disaster management?

Research methods that help to answer the sub-research questions are introduced in the following section.

3.2 RESEARCH METHODOLOGY & RESEARCH FLOW

This research will use different methods and combines these to ultimately answer the main research question. The sub-research questions are addressed by deploying a research method for each of them. In this chapter the research methods for each sub-research question are described, the data requirements and limitations of the methods are described, and an overview of the research is presented.

3.2.1 Identifying the requirements for modelling the network of communities and their reachability

To answer sub-research question 1, data needs to be gathered on what elements exist in a network where (international) aid is connected with communities victimised by a natural disaster, which is called the environment from now on. There is a need for information about what people exist in the environment, what characteristics are attributed to these people and what capabilities they have. Furthermore, there is a need for information about what organisations are involved and how they are connected to the environment. Lastly, there is a need for information about what infrastructures are involved in an environment, and what information is needed to model the infrastructures.

This data and information can be collected by conducting desk research. For conducting the desk research, scientific articles about infrastructural networks in natural disasters, relief organisations, and the use of graph theory in complex networks are consulted. This sub-research question is answered in Chapter 4 where the model is conceptualised.

This method of collecting information by desk research has as a limitation that it's difficult to capture all relevant information and to capture the whole spectrum of the network.

3.2.2 Determining the reachability of communities

To answer sub-research question 2, there is a need for insight in how the network (where (international) aid is connected with communities victimised by a natural disaster) works. This insight will be obtained by creating a model using graph theory. A Graph is a way of specifying a network by specifying the relations between different parts of the network (Easley & Kleinberg, 2010). Graphs can be used to create a mathematical model of the infrastructural network. An algorithm is created that allows creating nodes and edges from a graph and that allows calculations of different abstract network metrics, such as betweenness centrality, degree centrality and closeness centrality (Demšar et al., 2008). These abstract network metrics will be combined with enhanced network metrics, which are metrics that incorporate domain properties of the network. In this case, domain properties of the roads, communities (towns or cities) and airports. Also, path search algorithms will be used to determine the travel time of aid workers from airports or other logistical hubs to disaster victims. These measures will be used to identify critical nodes within a network and to identify the reachability of different nodes. When this is all set-up, it should be possible to insert input variables from realistic cases that drive the creation of the model and the calculations. The information that is required to use graph theory is the information that is gathered by the desk research to answer sub-research question 1. This sub-research question is answered in Chapter 5, where the configuration and implementation of the model is described.

The limitation of this method is that the model that is created will evidently be a simplification of reality. Its usefulness is dependent on assumptions that are made and on the availability of data. Therefore the results of the analysis with these graphs also might not be completely accurate.

3.2.3 Visualising vulnerability of communities based on reachability

In order to visualise the reachability of communities based on the previously described model with graph theory, an algorithm is constructed that takes the information of the model and combines this information with geographic information associated with the modelled network, and plots this on a geographic map. The information of the model that will be visualised consists of the different routes, special infrastructures such as airports, and the location of communities. The geographic information that is needed will be taken from OpenStreetMap, offering open-source geographic data. The result of the visualisation would be an overview of a region or country, where a user can view the criticality of airports in the region, and where a user can view with colours how reachable certain parts of the region are based on the reachability of these areas for aid workers. The results of the calculations in the graph theory part will be used to calculate a travel time value for each road that will determine the time it will take from an airport or another logistical hub to any other point in the network. Sub-research question 3 is addressed and answered in Chapter 7, where the visualisation process is described.

3.2.4 Using the visualisation to improve situational awareness

To answer sub-research question 4, the relevance and usefulness of the vulnerability visualisation are evaluated by doing a case-study on Sint Maarten and Papua New Guinea. The case-study on Sint Maarten is a relatively 'simple' case, because there is a lot of data available of the road network on street-level, while Papua New Guinea is a case with a lower data availability. The case-studies will serve to evaluate the technical feasibility of the artefact by reflecting on the ease of configuration of the artefact and making adjustments to the input of the model. Furthermore, the case-studies are used to evaluate the practical feasibility of the artefact. Conducting the case-studies analyses how well the artefact functions if deployed in practice and how decisions could be based upon the information the artefact yields. The infrastructure of the case-studies are modelled using graph theory and computations are conducted to determine the reachability of communities, criticality of airports and fragility of certain paths. The results are then visualised on a geographic map and on other informative plots. These visualisations are combined into a dashboard that gives an overview of the disaster context. Sub-research question 4 is addressed and answered in Chapter 7

Information that is required for this step in the research, is infrastructural information of both case-studies, topological information of the different communities and information about the airports (capacity, where it's located, and how vulnerable the airport is to disasters). This information is obtained by looking at literature about disaster management during Hurricane Irma, and during the Papua New Guinea earthquake in February 2018, and OpenStreetMap data of both areas.

3.3 SCIENTIFIC AND PRACTICAL RELEVANCE

The scientific contribution that this research aims to create is the design of a fast data-driven generalisable information system that improves situational awareness in a disaster situation. As mentioned in Chapter 2, in the disaster response in a sudden-onset disaster, information is essential for effective disaster management. Especially in the first days, it's important to have an overview of the disaster situation. This research shows a method to create this overview rapidly during the golden period of disaster response. This method is also generalisable to any disaster circumstance as the algorithm doesn't need to be adjusted for each context. Some other scientific contributions this research creates using graph theory while combining both topological metrics and intrinsic properties of a network, and combining reachability measures with humanitarian parameters to support decision-making in humanitarian crises.

Decision-makers and aid workers will be better equipped for sudden-onset disasters because they have more information readily available and this information dynamically changes as the situation changes with new information flowing in. This yields a dynamic and up-to-date representation of the situation allowing for better situational awareness. This enhancement in situational awareness is relevant because it will improve the effectiveness of disaster management. For disaster preparedness, the artefact may be used by decision-makers to pinpoint fragile points in their network and with that knowledge they can improve certain parts of infrastructure or increase the capacity of an airport if that improves the distribution of emergency supplies during a sudden-onset disaster. It also gives information about certain areas that are hard to reach when a disaster occurs, so that they might already store certain supplies beforehand.

3.4 RESEARCH FLOW

In Figure 3.2, an overview is illustrated of the different phases this research will go through. The first step is the problem formulation followed by the research formulation. After these phases have been finished, the environment will be explored, addressing sub-research question 1. The next phase involves the model design. The model design consists of two processes; the modelling of the environment with graph theory, and the visualisation of the model outcomes on a geographic map. The reachability model and its outcomes are evaluated by conducting two case-studies. After this, semi-structured expert interviews are conducted to evaluate the model usefulness. The model construction and evaluation is an iterative process that is used to refine the reachability model. This iterative cycle repeats until the quality of the model is considered sufficient. This leads to a conclusion, which includes an answer on how analysis of the reachability of affected communities in a disaster may improve situational awareness.

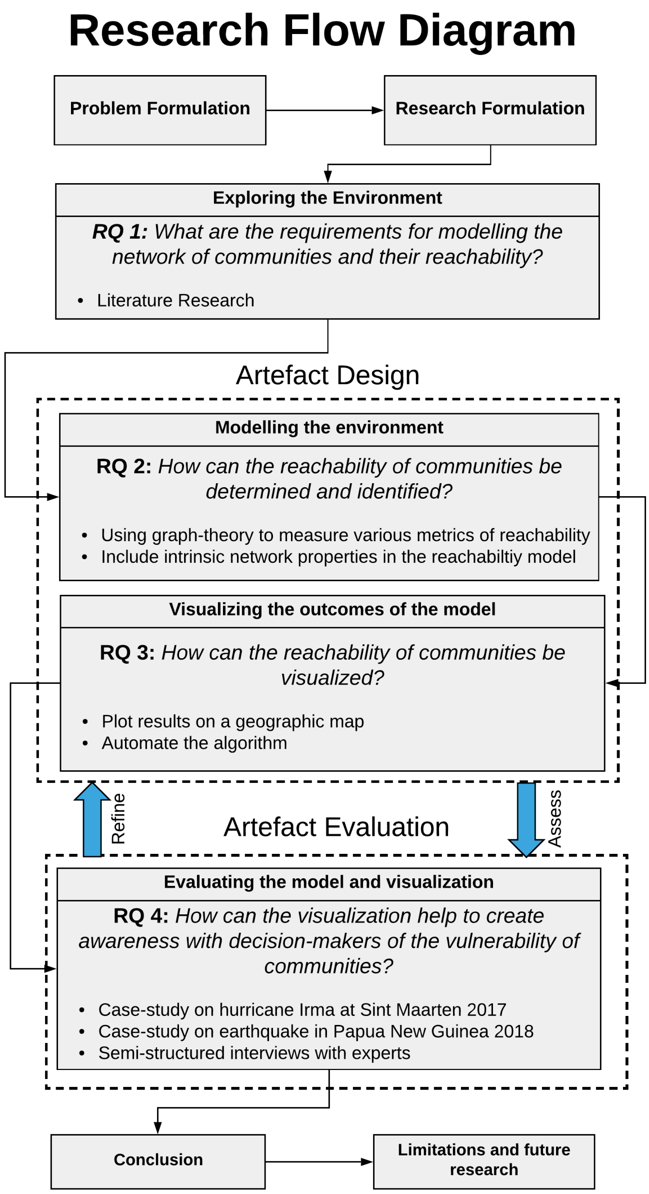

Figure 3.2: Research Flow Diagram

4 CONCEPTUALISATION OF THE MODEL

"The science of today is the technology of tomorrow"

Edward Teller

The reachability model is conceptualised in this chapter. The conceptualisation consists of the exploration of all the requirements needed to construct the model. The design framework of Hevner et al. (2004) is used for the conceptualisation of the model. A conceptual overview of the reachability model is illustrated in Figure 4.1. The first step of the design is to explore graph theory in complex networks and the measures that could be relevant for the model. The second step of the design is to explore the environment in which the model is to be used and the relevant requirements for modelling a road network of a region that connects international aid with communities in the region. The third step is to identify the knowledge base by determining how graph theory is deployed, what metrics are to be used and what type of visualisations are relevant for the objective of this research. The Information Systems research framework of Hevner et al. (2004) in Figure 3.1 shows that information systems research is driven by the needs of the environment and applicable knowledge from the knowledge base. As mentioned before, the interaction between the environment and the artefact is known as the 'relevance cycle'. This basically means that the environment determines the requirements for the artefact and the artefact is evaluated by application to the environment. The 'relevance cycle' iterates between the development of an artefact and the evaluation of an artefact until a satisfactory artefact is developed. The interaction between the knowledge base and the artefact is known as the 'rigour cycle'. The knowledge base offers scientific theories, foundations and methodologies that can be used for the development of an artefact. The 'rigour cycle' is complete when a complete artefact makes additions to the knowledge base by creating scientific added value. In this research, the mentioned artefact is the reachability model and its visualised outcomes.

4.1 USING GRAPH THEORY IN DISASTER-STRUCK AREAS

Graph theory analysis can be used to reduce the unpredictability of a sudden-onset disaster by having road network characteristics and community reachability information readily available. This could increase the situational awareness of relief organisations and aid workers, making better disaster management possible.

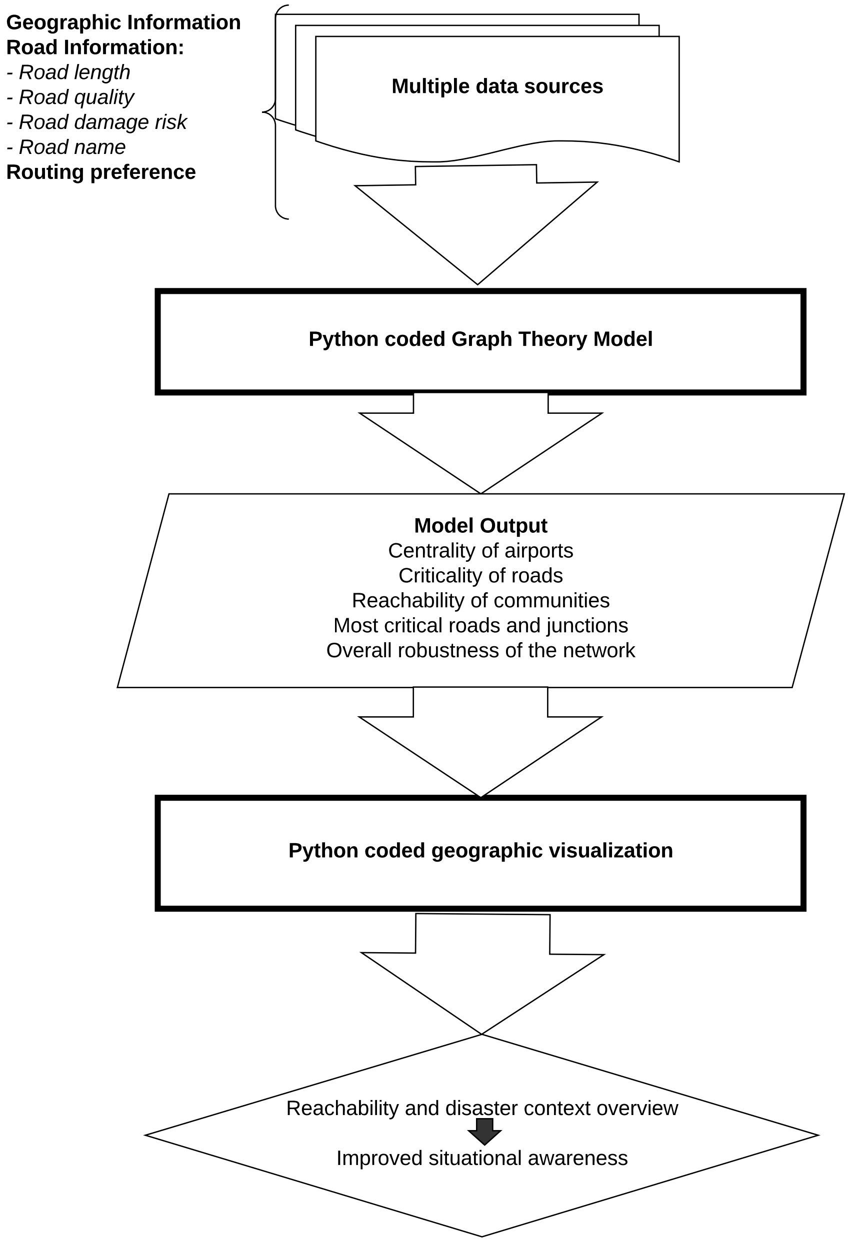

Figure 4.1: Conceptual Diagram of the modelling process

4.1.1 Complex networks

According to Guimerà, Sales-Pardo, and Amaral (2007), real-world networks are mostly complex networks. Complex networks are generally large in node number and sparse at the same time (Strogatz, 2001). Furthermore, in complex networks, the structure affects the dynamic function of the system (Newman, 2003). Kalapala, Sanwalani, Clauset, and Moore (2006) argue that for sufficiently large geographic areas, degree distribution of nodes in a graph follows a power law, meaning that there are many nodes only a few connecting edges and a few nodes with many connecting edges (Derrible & Kennedy, 2011). Li and Han (2017) shows an example where an urban road network is classified as a complex network because the distribution of the node degree follows a power law, the average path length is small and the aggregation coefficient is large. Therefore, an infrastructural network of a region or country that connects different communities with (international) aid via an airport is assumed to be a complex network.

4.1.2 Assessing critical infrastructures in networks

When a sudden-onset disaster strikes, transportation networks are crucial for the response and reconstruction of the post-disaster area. The transportation network is used for the evacuation of victims, transportation of goods, or mitigating dangerous situations in the disaster-struck area (Mitsakis, Salanova, Stamos, & Chaniotakis, 2016). Literature suggests that graph theory is a suitable method to analyse networks and identify the connectedness of parts in the network (Zeng & Church, 2009; Mitsakis et al., 2016; Demšar et al., 2008; Schintler, Kulkarni, Gorman, & Stough, 2007). Graph theory is used to describe physical systems whose performance depends on their components and the relative location of these components (Kaveh, 2013). The topology of the structure of a network influences the overall performance of the network.

According to Mitsakis et al. (2016), centrality measures of graph theory can be used to identify important network segments, offering fast indicators that are suitable for real-time analysis during or after a sudden-onset disaster. Centrality measures are metrics that represent the structural importance of an edge or a node in a network. The level of centrality indicates the impact of one node on other nodes (Demšar et al., 2008; Hernandez & Van Mieghem, 2011). Commonly used centrality measures are degree, closeness, betweenness and edge-betweenness centrality. The degree of a node is the number of nodes it is directly connected to via an edge. The closeness of a node is the shortest distance of the node to every other node. The betweenness centrality is a measure of the number of shortest paths of every pair of nodes that run through a specific node or edge relative to the total number of shortest paths (Demšar et al., 2008; Hernandez & Van Mieghem, 2011). The mathematical illustration of betweenness centrality is shown in Equation 4.1.

$$b(v) = \sum_{s \neq t \neq v} \frac{\sigma_v(s,t)}{\sigma(s,t)} \qquad (4.1)$$

Where s and t are two different nodes of the graph that are not the same as node v for which the betweenness is calculated, which would be the airport in this research, and where $\sigma_v(s,t)$ is the number of shortest paths from s to t that go through v, and where $\sigma(s,t)$ is the total number of shortest paths between all nodes (Demšar et al., 2008; Hernandez & Van Mieghem, 2011). The edge betweenness is defined as the number of shortest paths between any two nodes that go through an edge (Girvan & Newman, 2002). The edge betweenness illustrates the importance of an edge.

Demšar et al. (2008) agree with the usefulness of centrality measures and concludes with his research on dual graph modelling applied on the network of the Helsinki Metropolitan Area, that the betweenness centrality and cut vertices prove to be the most useful properties for identifying critical locations in networks. Schintler et al. (2007) have developed an approach for analysing the resiliency of transportation networks based on graph theory by using raster-based GIS techniques. This method allows for identifying critical nodes or links in a network that have spatial interdependencies with other networks and it also captures the spatial detail of a network. Moreover, Wagner and Neshat (2010) use graph theory to quantify the vulnerability of supply chains and they demonstrate that graphs can be used as visual maps that make the understanding of vulnerability easier which supports decision making.

These authors offer interesting insights into methods and metrics to identify critical locations in a complex network. When looking at the transportation network of an area struck by a sudden-onset disaster, these insights could prove useful for evaluating whether an airport is critical. A limitation of the research of Demšar et al. (2008) is that the analysis of complex networks is solely focused on topological information to identify critical infrastructures, while specific attribute information of certain locations is not used. In the case of airports in a disaster-struck area, this specific attribute information is quite important in deciding the criticality of this airport. Research of Guimerá and Amaral (2004) describes a method to identify critical airports using degree centrality and betweenness centrality, but does it solely in the context of inter-airport connectivity and does not discuss how to identify a critical airport in terms of connectivity with communities on the surface, relying on relief supplies flowing through that airport. Schintler et al. (2007) look solely at the overall performance or resilience of the road/rail networks and the impact of disruptions on specific segments, but it doesn't look into the vulnerability of certain segments of the networks as a consequence of disruptions. Looking into the vulnerability of certain segments is relevant when considering a network in the context of a sudden-onset disaster because these segments in the network could be part of a community. Mitsakis et al. (2016) do consider a complex network in the context of sudden-onset disasters but does not illustrate the impact disruptions could have on specific communities. It takes the perspective of the emergency relief organisations looking at the overall functioning of the road network on behalf of humanitarian aid, but it doesn't give insight in how to map the vulnerability of communities as a result of high dependence on an airport for relief supplies.

4.1.3 Complex network measures

As mentioned already in the previous paragraph, a limitation of most research on the analysis of complex networks is that it's often solely focused on the topological information of the network. Specific domain properties can be very relevant when analysing a network because these properties can determine the importance of elements in the network, even though they might not seem important when solely looking at topological information. In research, it has been found that topological metrics alone are not sufficient in capturing essential information of a network (Ellens, Spieksma, Van Mieghem, Jamakovic, & Kooij, 2011; Bompard, Wu, & Xue, 2011; Koç, Warnier, Kooij, & Brazier, 2013). A nice example is discussed in research of Ellens et al. (2011) where the authors came up with effective graph resistance as an enhanced metric that captures the accumulated effective resistance between all pairs of nodes within the network of a power grid. Similarly, Bompard et al. (2011) use an extended topological method by incorporating specific features of a power system, like electrical distance, power transfer distribution factors and line flow limits. Also, Koç et al. (2013) propose a new metric combining structural aspects of a power grid with properties of the operative state of the power grid. There is also research on the use of complex network measures in road networks. Research of De Montis, Barthélemy, Chessa, and Vespignani (2007) studies the structure of the road network in Sardinia, combined with statistical properties of commuting traffic. These findings do not discourage the use of topological metrics in analysing networks. However, these findings do suggest that the incorporation of domain properties of the network could give a deeper insight into the network. Especially when combining topological metrics with domain properties of the network.

When analysing the connectedness of communities with nearby airports in a disaster-struck area, it is relevant to not only focus on the structural features of the network that determine connectedness, but also the domain properties, following the practice of the literature discussed in the previous paragraph. For the analysis of a road network connecting airports with communities, the relevant domain properties that can be incorporated are specific features of the roads, airports and the communities.

4.1.4 Analysing network connectivity

Analysing the reachability of communities by aid workers requires insight in the connectedness of these communities along the network they're connected to. In graph theory, there are many ways of calculating how well-connected certain segments of a network are. Albert, Jeong, and Barabási (2000) explain their use of the connectivity metric to analyse error tolerance in a variety of systems. Connectivity of any pair of nodes in graph theory is defined as the number of edges that need to be removed to disconnect this pair of nodes from each other. The higher the value for connectivity, the stronger the connection between a pair of nodes (Bondy & Murty, 1976; Esfahanian, 2013). The value of connectivity lies in the potential to identify how (dis)connected communities are in relation to a nearby airport.

There are more ways of determining the connectedness of communities with airports. Dijkstra's Algorithm is an algorithm that finds the shortest path between two nodes in a network (Jasika et al., 2012). Dijkstra's algorithm is often applied in road networks, because Dijkstra's algorithm is meant to handle positive edge weights (Cherkassky, Goldberg, & Radzik, 1996).

4.2 EXPLORING THE ENVIRONMENT OF THE PROBLEM SPACE

The exploration of the environment of the problem space means in this research that the environment that will be modelled in this research needs to be identified focusing on the decision-makers and their objectives, relevant elements of the network and the required information that is necessary for the reachability model to be used. The problem space in this research is in the pre-disaster phase (Duran et al., 2013), as the objective of this research is to design a reachability model that supports the situational awareness during the response to sudden-onset disasters. The problem space is located in a region and specifically in a physical infrastructural network consisting of roads, airports, and communities in either cities or villages. The infrastructural network connects communities and airports with roads. The decision-makers are people and organisations that are involved in the disaster response phase and have certain interests and objectives. For this situation to be modelled and visualised, the relevant entities are identified in this section and also the required data is identified.

4.2.1 Relevance of this research for decision-makers

The decision-makers that are involved in the disaster response phase are either organisations or individuals. According to the Decision-Makers Taxonomy of Verity Think (2013) the decision in disaster management are a wide variety of organisations and individuals that can be grouped into individuals, non-governmental organisations, military, international organisations, the private sector, donors, the public sector and the media. The decision-makers taxonomy is illustrated in Figure A.1 in Appendix A. The stakeholders and their objectives relevant to this research are also described in Appendix A.

This research revolves around the development of a reachability model that helps to map the reachability of individuals in communities for relief efforts in times of a sudden-onset disaster in order to support situational awareness. Mapping the reachability could support the situational awareness for relief organisations when responding to a sudden-onset disaster. This aim for the improvement of situational awareness is in line with the objectives of the individuals, non-governmental organisations, military, international organisations, donors and the public sector as mentioned previously. Therefore the relevance of the to-be-constructed reachability model is based on the objectives of the stakeholders. Outcomes of this research could be especially interesting for relief organisations because it supports situational awareness which is of crucial importance for the relief operations carried out by these organisations during the response phase of sudden-onset disasters. Furthermore, it's interesting for the public sector, because it analyses where the road network might need improvements, but also for private organisations such as airports because the reachability model shows which airports may be most suitable for the distribution of relief supplies. This is part of the relevance cycle as proposed by Hevner et al. (2004), which relates to the application of the designed reachability model in the environment.

Furthermore, the relevance of this research is also consistent with the Sendai

Framework for Disaster Reduction (UNISDR, 2015), which is a framework that is endorsed by the UN General Assembly following the 2015 Third UN World Conference on Disaster Risk Reduction. The Sendai Framework aims to guide the management of disaster risk in development at all levels and across all sectors. The framework proposes several targets and priorities that guide actions toward disaster risk reduction as described in Figure 4.2. From the four priorities for action presented in the framework, "Priority 1: Understanding disaster risk", relates to this research. Priority 1 is focused on the pursuit of knowledge for the implementation of appropriate preparedness for disasters (UNISDR, 2015). The reachability model that is constructed in this research plays into this priority by analysing the reachability of communities and therewith supporting decision-makers in the implementation of appropriate preparedness to disasters by having a tool that allows for greater situational awareness as soon as a disaster occurs. Using graph theory and a geographical visualisation helps to become aware of the situational context and how a disaster situation develops over time. Ultimately, this research supports reaching one of the Sendai Framework's targets, that is to substantially reduce the global disaster mortality rate, as a consequence of improved situational awareness because of insights the constructed reachability model in this research yields.

4.2.2 Relevant elements in the network

The network of a country or a region needs to be modelled using graph theory capturing all relevant elements of the network. The network is focused on the connection of communities with a nearby airport or another entry point, that allows them to receive relief supplies during the response phase of a sudden-onset disaster or to be evacuated to a safe area. Airports and other entry points are assumed to be of importance in such a network because they allow relief supplies to be flown in, and evacuees to be flown out. These communities are connected to nearby airports with roads that form a road network. Airports and other entry points are to be represented as nodes in the network. Roads that connect the nodes are considered edges in the model. Roads have an associated travel time (for different modalities), capacity and quality that are included in the model. All these elements are both relevant for the graph theory model and the visualisation.

4.2.3 Required information for the reachability model

To model the network of a country or a region with the aforementioned elements, data is needed for the different elements. The first important step is to know what geographic area is to be modelled. When this is determined, data needs to be collected on how many communities and airports there are in a region, and how these airports and communities are connected, with how many roads on what distance. Furthermore, the amount of people living in a community needs to be known and the capacity of an airport. Also, the infrastructural quality of roads, travel time on the road for trucks, and the risk of being damaged by a sudden-onset disaster need to be known. For the visualisation to be executed, the previously mentioned data needs to be integrated with geographic information (such as coordinates), a geographic map of the region and shape-files of areas where communities live in the region. The outcomes of the graph theory model are also necessary for further visualisation of the network.

Figure 4.2: Chart of the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015)

4.3 EXPLORING THE KNOWLEDGE BASE

For the model to be constructed, it's necessary to explore what theories, methods and metrics are relevant to use for this research. Furthermore, in this section, the role of visualisation of the reachability of communities is motivated and different ways of visualising a network is discussed.

4.3.1 The role of graph theory

In this paragraph, the role and the relevance of graph theory for mapping the reachability of communities by humanitarian aid or evacuation support during sudden-onset disasters, metrics available in graph theory and their usefulness are discussed. This section will conclude with a motivation that explains the usefulness of graph theory for this research. The basic principles of graph theory are described in Appendix B.

To determine how well-connected communities are with nearby airports and how robust this connection is, suitable metrics need to be deployed to calculate this. There is a wide variety of metrics available in graph theory and the suitability of several of them for this research is discussed. First, centrality measures are discussed. Second connectivity is discussed as a metric. Third, intrinsic properties are discussed and lastly, path search algorithms are discussed.

Centrality measures
The centrality measures that are incorporated in the graph theory model are the node betweenness centrality and edge betweenness centrality. The node betweenness centrality indicates the number of shortest paths between any pair of nodes crosses a certain node and the edge betweenness centrality indicates the number of shortest paths between any pair of nodes crosses a certain edge. This centrality measure how centrally located a certain node or edge is in the network. The betweenness centrality is calculated for each node and edge and then added as an attribute for each node and edge.

Intrinsic network properties:
The previous metrics are purely topological measures and lack intrinsic information of the network elements. The model includes intrinsic properties of the network as attributes to the edges in the graph to create a more representative model. The intrinsic properties of the network that are included are features of the roads in the network. Intrinsic network properties that are included in the model are the length of a road segment, the maximum speed that can be driven on a road segment, the quality of a road segment, the number of lanes on a road segment and the time it takes to cross a road segment completely. All these features are captured in the attribute of the edges within the model.

Path search algorithms
Path connectivity between an airport and any community gives relevant information about the reachability of communities. In order to find the shortest path (in terms of time), Dijkstra's algorithm is used to evaluate the shortest path length between the airport and every other community. Dijkstra's algorithm will help to identify the distance of an airport to other communities based on the intrinsic road properties previously discussed. These

road properties will determine how Dijkstra's algorithm finds the shortest path and how long this path is. When applying Dijkstra's algorithm for the airport with each of the communities, an overview can be created of the reachability of communities.

It can be concluded that graph theory and the aforementioned metrics and path algorithms are relevant for this research as it will analyse the importance of all elements in the network. Using a combination of all the metrics allows for identifying the reachability of communities and improving the situational awareness during a sudden-onset disaster.

4.3.2 The role of visualising the reachability of communities

Previously in section 2.5 it is discussed that geographical visualisations in the context of sudden-onset disasters have a high relevance for disaster management. Among stakeholders in different contexts, there is a growing demand for spatially-explicit information on a local scale. Especially regarding the vulnerability of people to climate change (Preston et al., 2011).

A visualisation is required of a road network where the reachability of segments in the network is easily visible, showing multiple levels of detail. Furthermore, it's relevant to be able to identify the most important crossings and roads in a network as well, to give a deeper understanding of the network. Besides the reachability, an overview of the road quality combined with the importance of these roads is also of relevance to visualise. Moreover, these visualisations need to be able to adapt, as the data develops over time. These changes need to be visible. Information about the network as a whole should also be visualised by using plots to indicate structural properties of the network, but also to identify the structural importance of the airports.

Such visualisations could be created using the generated information in the graph theory model and use isochrones to visualise the outcomes of the model. Isochrones can indicate areas that are within a similar reachability range. These can be used to visualise the reachability for a number of radii on the geographic map. The visualisation of the outcomes will be helpful to create enhanced situational awareness during sudden-onset disasters.

Ultimately, all visualisations are to be combined into a dashboard that includes all visualisations and related information. A dashboard offers an overview where all information is centred in one place that could be used in the field.

4.4 SYNTHESIS OF THE CONCEPTUALISATION

In this chapter, the conceptualisation of the reachability model is discussed by getting to understand the environment in which the reachability model is to be applied, including the stakeholders, and by getting to understand the knowledge base that is consulted for the development of the reachability model. Both of these parts are the building blocks of the information system research. Figure 4.3 illustrates how the framework of Hevner et al. (2004) is applied to this research.

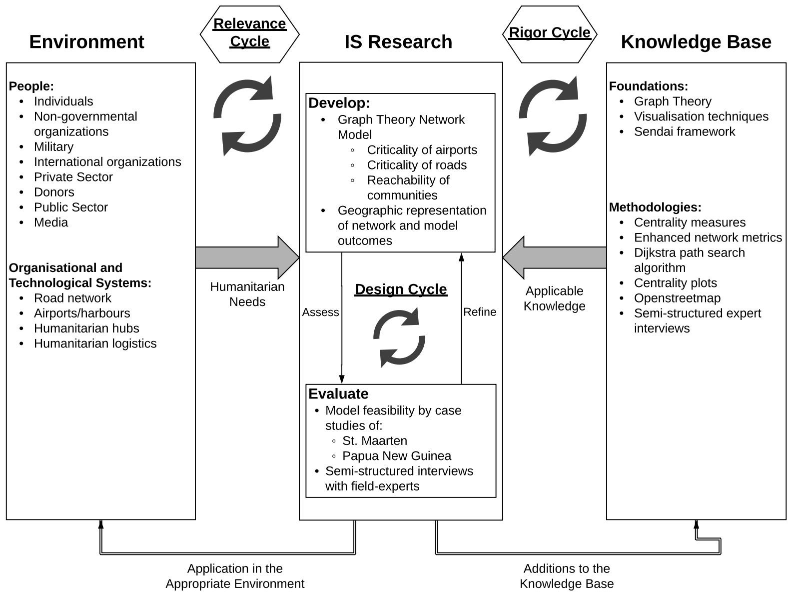

Figure 4.3: Hevners Framework Applied to this research (Hevner, March, Park, & Ram, 2004)

To develop the reachability model, the knowledge base offers graph theory with several metrics and visualisation methods. Graph theory is used to measure the reachability of communities. The metrics used for this are several centrality measures, intrinsic network properties and path search algorithms. For visualising the network, isochrones are used to visualise reachability and the visualisations are combined into a dashboard. This chapter presents the building blocks for the reachability model. In the next chapter, the building blocks are combined to construct the reachability model, which is a visual representation of a road network, illustrating the reachability of communities for relief aid, which could ultimately support situational awareness in disaster response.

5 MODELLING REACHABILITY WITH GRAPH THEORY

> "The goal is to turn data into information, and information into insight."
>
> *Carly Fiorina*

This chapter describes the construction of the model that analyses the reachability of communities during natural disasters in the very beginning of the response phase. In the previous chapter, the requirements that need to be met in order to construct the model are determined. Chapter 4 presents insights into how graph theory can be used effectively for this research. The building blocks for the model have been conceptualised so that in this chapter the model can be constructed. In this chapter, the whole modelling process is described sequentially. For some of the processes in the model construction, a mathematical illustration is given in Appendix E. After the model construction, a thorough description of how the model has to be used is given, explaining how structural changes in a network are to be implemented in the model, what ways of routing could be done in the model and how to handle updates of information. Thereafter, the implementation of the model in Python is explained and a verification of the pre-defined processes is elaborated on. All elements of the detailed process diagram are discussed one by one in this section to describe how the model is constructed. The processes that take place to create the reachability model are explained sequentially. For each process that is explained, the inputs and the outputs, and how these relate to each other are described.

5.1 MODEL CONSTRUCTION

The process diagram in Figure C.1 located in Appendix C, illustrates a detailed overview of how the reachability model is constructed, based on the conceptualisation in the previous chapter. This figure shows how all the inputs are processed into enriched information, that is in turn used in other processes, leading to a multi-directional graph network with relevant attribute information that can be visualised to illustrate the community reachability. This detailed process diagram is divided into four main processes as illustrated in the general overview of the modelling process in Figure 5.1. The divided processes are the data import, the configuration of the network graph, calculating the reachability and visualising the reachability. The first three of these processes are further specified in this section. The reachability visualisation is elaborated on in the next Chapter.

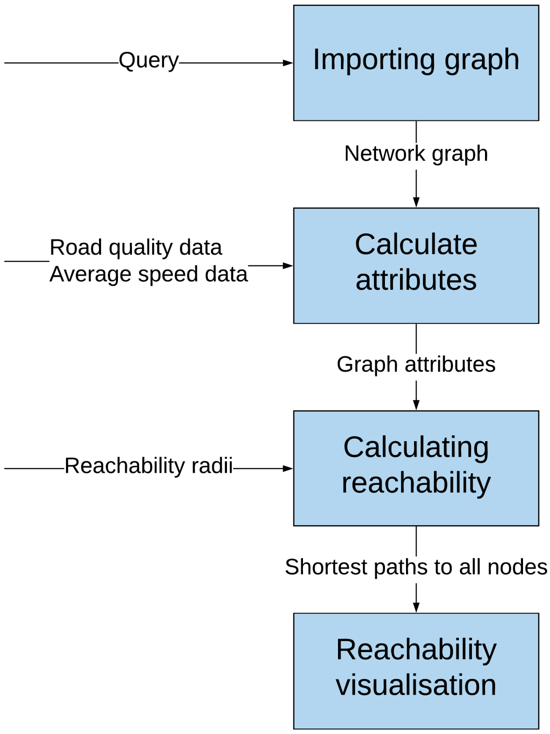

Figure 5.1: General overview of the four phases of the modelling process of the reachability model

5.1.1 Importing graph network from OpenStreetMap

The phase in the modelling process is importing the graph network from OpenStreetMap. This phase consists of four processes that are illustrated in Figure 5.2.

Importing geographical data from OpenStreetMap

The first step is to determine for which location the model needs to be constructed. When a location is determined, the geographical data of the specified location needs to be imported from OpenStreetMap. OpenStreetMap is an online mapping tool that is built and maintained by a large community of mappers (OpenStreetMap, n.d.). The power of OpenStreetMap is in the emphasis of local knowledge, which can be a great advantage in areas where governmental road network administration is not properly maintained. Also, in natural disasters, the state of a road network may change drastically, where OpenStreetMap allows changes to be made by local observers that have first-hand information about the developments. Furthermore, its data is available to anyone for free.

The input of this process is a query where a location is specified. When a query is specified, the information of the query enters the process of the import of geographical data from OpenStreetMap. The process uses the query information to get the most recent geometry data of the administrative boundaries of the desired location from OpenStreetMap. The geometry data of the desired location is stored.

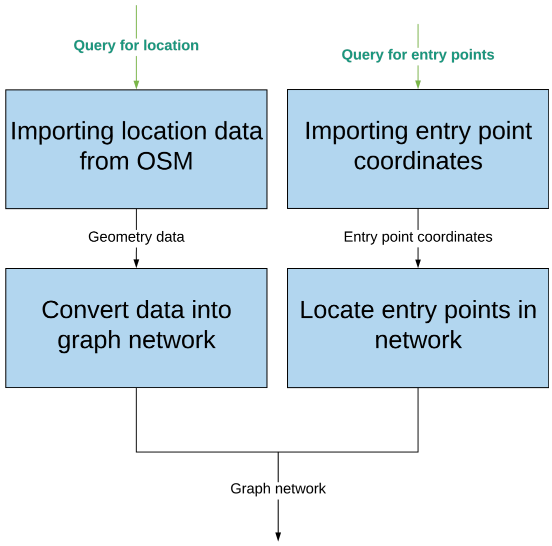

Figure 5.2: Four processes that are required to import the geographical data of a road network from OpenStreetMap and to create a graph network. The green arrows are the manual input, which are respectively the location query and the entry point query. The output of this overall process is a graph network of a specified location including identified entry point nodes.

Converting geographical data into a multi-directional graph network

The next step is the process where the geometry data acquired in the previous process is converted into a multi-directional graph network. The input for this process is the geometry data of the location, and the desired output is a multi-directional graph network. A multi-directional graph network is a directed graph class that is able to store more than one edge between any pair of nodes and it also allows self-loops. A multi-directional graph is ideal for a physical street network because in these networks self-loops and multiple edges per node pair occur frequently. From now on, the multi-directional graph network will be referred to as the 'graph'.

The geometry data of the desired location as previously produced determines that the road network that needs to be imported from OpenStreetMap needs to be within the defined administrative boundaries of the desired location. This network needs to be imported from OpenStreetMap and a graph needs to be constructed by placing a node on each intersection and an edge between all nodes that are connected based on the network data. All nodes and edges are accompanied with several attributes that give additional information about it, such as the identifier of a node or edge, the length of an edge, the name of a street that is represented by an edge and more. The output of this process is a graph network of the queried location which is basically a collection of data about nodes and edges, including actual coordinates so that it's consistent with the actual network.

Importing geographical data of entry points from Openstreetmap

For the sake of this research, it's relevant to identify entry points in the network that are used to calculate the reachability from. In order to import the coordinates of entry points of interest, a query for entry point locations needs to be specified. This query serves as input for the main process where this query is converted into the coordinates of the desired entry points. Also, this process consists of importing data from OpenStreetMap. The output of this process is are coordinates of one or more entry points which will be stored.

Locate entry point nodes in the graph network

The entry point coordinates from the previous process are used as input for the process of locating the nodes in the constructed graph network that are closest to the entry points. As all the nodes in the graph network carry information about their coordinates, the node that is closest to the coordinates of an entry point will represent that entry point in the network. In order to find this node for each of the specified entry points, the distance between an entry point and each of the nodes in the graph needs to be calculated. The node which has the shortest distance will then become the entry point's node. The distance is calculated by comparing both the latitude and longitude of the entry points with the coordinates of all other nodes. In order to find the shortest distance between two points on earth, it needs to be considered that the earth is a sphere, which requires calculating the 'great circle' distance between the coordinates. The great circle distance between two points on a sphere is calculated using the Haversine formula (Gade, 2010). The mathematical illustration of this process is explained more thoroughly in Appendix E.1

This process finds a node in the graph network that is the closest to the entry point. The closest node is then identified as the node representing this entry point. When this operation is done for the first entry point, it repeats for each of the other entry points. The output of this process is entry point node information that is stored in the graph.

5.1.2 Calculating graph network attributes

The second phase of the modelling process is where different attributes of the network need to be used to calculate other attributes that are required for the reachability model. This phase consists of three processes, one that calculates the travel time for each edge, another to calculate the flow time of each edge, and the last one to calculate the betweenness centrality of the edges and the nodes, while identifying the betweenness centrality for the specified entry points. This phase is illustrated in Figure 5.3.

Calculate the travel time for each edge

To calculate the travel time to cross each edge, the previously acquired information that is stored in a multi-directional graph is used. The travel time depends on the length of an edge, the speed with which an edge can be crossed and the quality of the road represented by the edge. The inputs of this process are the road length, the maximum speed on a road, average speed information and road quality information. The road length is an attribute carried by all edges in the graph as determined in OpenStreetMap and it indicates the length of road in meters. The average speed information is data that needs to be inserted manually. This indicates the average speed in kilometres per hour an aid worker may travel in ideal conditions.

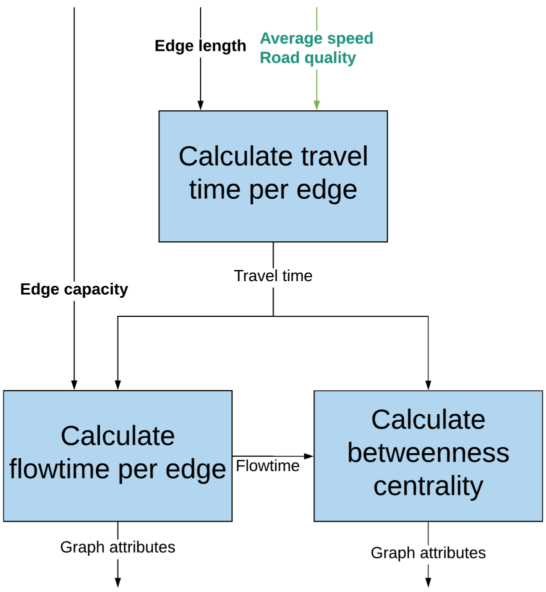

Figure 5.3: Processes required to calculate the graph network necessary graph attributes. The arrows with bold text illustrate input that comes from the previous phase, which is the edge length and edge capacity. These are attributes that come from the constructed graph. The green arrow with green text is manually input data that is specified by the user. The overall outcome of this process is further calculated and specified graph attributes.

The maximum speed on a road is information that is available for some of the edges in the graph. When this information is available, it is used in the calculation to calculate the travel time, when it's not available, the average speed is used in the calculation. The road quality information can be inserted into the process when there is available data about the road quality. The road quality should be a value between 0 and 1, where 0 is the lowest possible road quality meaning that the road is completely inaccessible, while 1 is a perfect road quality, making it possible to drive at the maximum speed. When no information is available about the road quality, the value for road quality is set to 1. When this information is or becomes available, this information can be inserted into the model.

The travel time per edge is calculated by first converting the specified travel speed (either the average speed or the maximum speed attributed to the edge) into meters per minute, as the road lengths are in meters. From now on the travel time will be measured in minutes for practical purposes. Then the travel time is calculated by dividing the length of an edge by the product of the specified travel speed in meters per minute on that edge, and the road quality function. The road quality function follows an S-curve between 0 and 1, implying that when the road quality is 1, the maximum speed can be driven on that edge. When the road quality drops, the impact of the road quality on the speed accumulates for each unit of change until it reaches 0.5. Then the change in speed per unit change in road quality slows down. This operation is conducted for all of the edges and the travel time is stored as attribute information of the edges in the graph network. A mathematical description of this process is described in Appendix E.2.

Determine the flow time of all edges

A combination of the time it takes to cross an edge and with how many vehicles this can be done simultaneously is called 'flow time'. The flow time is a metric that divides the time it takes to cross an edge by the number of lanes. The flow time represents the flow of goods per time unit on a road. Flow time can be used as a routing option in the reachability model. Making roads with higher capacity more attractive to choose when looking for the shortest path compared to roads with lower capacity.

Compute the edge-betweenness centrality

The next computation that is conducted on the graph network is computing the betweenness centrality of the edges. This is a topological metric that gives information about the structural importance of the edges. The input of this process is the travel time of each of the edges, as this information is used to determine the shortest paths.

The subset edge-betweenness for all shortest paths between the entry points and all other nodes is calculated, where the subset consists of a set of source nodes, which are the entry point nodes, and all other nodes are the targets. The subset edge-betweenness centrality gives insight into the criticality of the roads in terms of reachability of each of the entry points by other nodes. The higher the edge-betweenness centrality, the more critical the road is for travelling between any node and one of the entry points. In other words, when the edge-betweenness centrality is high, it means that the road plays an important role in connecting the network.

The equation for edge-betweenness centrality is used for a subset of nodes and the shortest path is determined based on the travel time that has been calculated previously. The shortest path is the path with the lowest travel time. The equation illustrating this process mathematically is described in Appendix E.3. The output of this process is the subset edge-betweenness centrality, which is stored as an attribute for each of the edges in the graph network.

Compute entry point betweenness centrality

The entry point nodes are part of the network and their structural importance also needs to be calculated. To determine the structural importance of the entry points, the betweenness centrality of the nodes of all entry points is calculated. The betweenness centrality of the entry points indicates how well-located the entry point is within the network. The higher the betweenness-centrality, the better the entry point is located to be reached by any node in the network. The input of this process is the travel time of the edges, which is used in the process to find the shortest paths. The shortest path is the path with the lowest travel time. The equation is described in Appendix E.4.

When this equation is conducted, the outcome will be the betweenness centralities for all nodes. To identify the betweenness centrality of the entry points, the node identifiers of the entry points as found in section 5.1.1 are used. The information of the betweenness centralities of the entry points and all other nodes is stored in the graph network.

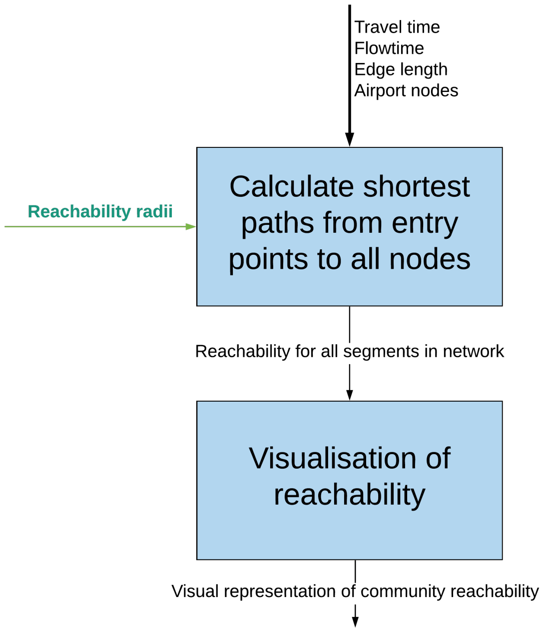

Figure 5.4: Process of calculating the reachability: the green arrow with green text is the manual input of the reachability radii, specified by the user and the bold arrow above is input that comes from the previous phase, which are attributes that have been calculated previously.

5.1.3 Determine reachability from entry points to all nodes

The reachability is determined by calculating the travel time from the entry points to all nodes in the network. Dijkstra's shortest-path algorithm is used to calculate the shortest distance to any nodes using either the travel time, edge length, or flow time as the weight. This step prepares for the visualisation utility of the model. In this research, the reachability is mapped by evaluating which nodes can be reached from each entry point within a certain travel time or distance. In this model, a list of radii is to be inserted as the input of this process and based on the radii the reachability of nodes within this radii is calculated. The list of radii can be for example: [20, 40, 60, 80, 100, 120, 140]. When these radii are inserted, the nodes that can be reached within 140 minutes from entry point 1 are identified, then the nodes that can be reached within 140 minutes from entry point 2 are identified, and so on. When all entry points are iterated over, the nodes that can be reached in 120 minutes by entry point 1 are identified, and so on. Ultimately, there is insight in which nodes are reachable in what travel time by which entry point. This information will serve as input for the visualisation aspect of the artefact. The visualisation aspect of the artefact will be dealt with in the next chapter.

5.2 INTENDED MODEL USE

The multi-directional graph is now constructed and it includes attribute information of both the edges and the nodes. Moreover, information is obtained about which nodes exist in a certain radius around each of the entry

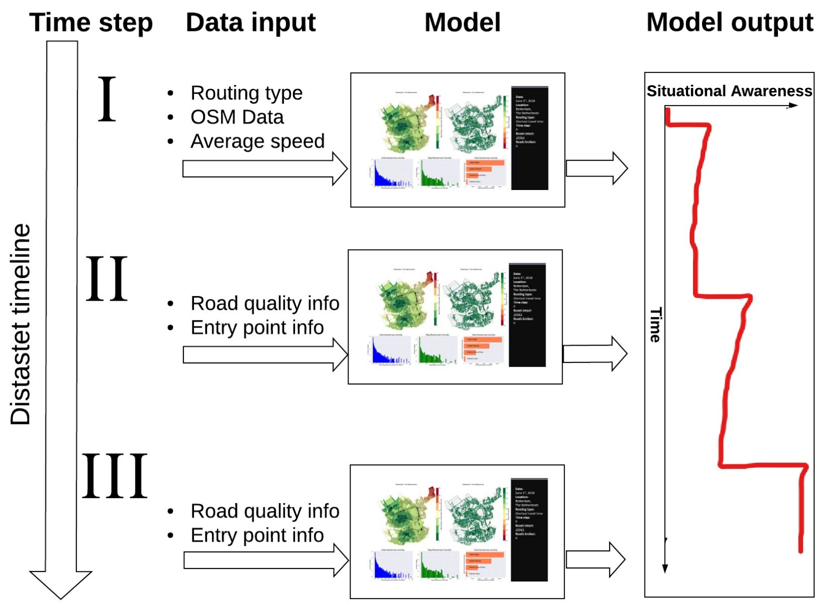

Figure 5.5: Illustration of the intended model use.

points. The graph can be used to calculate the reachability of communities in sudden-onset disasters and an important aspect of the constructed graph, is that it's data-driven. As information changes or more information becomes available, the graph can be refreshed so it includes more accurate information. In this section, the use of the model explained by elaborating on how the graph can work with structural changes in the (real) road network during a sudden-onset disaster and what different ways routing could be used. In Figure 5.5, the use of the model is illustrated in a diagram. It shows that the model evolves as the disaster situation develops over time. In the first time step, the routing type of the reachability map is chosen and the initial road information is inserted, creating a model of the reachability of a network. The output of this model is an initial state of situational awareness, based on the information that's available at the beginning of the disaster response phase. As time goes by, more information becomes available and can be inserted into the model, leading to an improved situational awareness. This goes on until the response phase ends. The red line in the red box on the right illustrates a hypothetical advancement of the situational awareness over the disaster time-line.

5.2.1 Structural changes during disasters

When a sudden-onset disaster occurs, there is often barely information available about the situation. The model can then be used to obtain preliminary insights into the road network and the reachability of communities in the default situation. When more information becomes available about which entry points will be used and can't be used, and what roads or bridges are damaged and to what extent, this information can be used as input in the model, improving overall situational awareness in the disaster situation. One of the strong suits of the model is that it's able to adapt easily to changes that occur in the network.

Initially, the graph will be created based on the road network as available in OpenStreetMap. If there is information available about which entry points are going to be used and which will not, the right entry points can be selected within the graph to base the calculations on. When there is new information about structural changes of the network, such as a bridge that has collapsed and has become impassable, the manual road quality input should be adjusted. When the road quality of the collapsed bridge is set to 0, the graph will be constructed including the fact that the bridge can't be used any more. This will yield different outcomes of the calculations and reachability of communities in the network. It will also yield different outcomes of the betweenness centralities of the entry points and the average betweenness centrality of all nodes. Furthermore, it will change the edge betweenness centralities as a result of the different shortest routes that appear.

The model adapts to changes in the network, as long as the new information is inserted into the model. This may be useful, as it will allow relief organisations to create an overview of the situation in the first minute, even though there isn't any information about the disaster yet. The relief organisations can then already draw (careful) conclusions.

During an ongoing disaster response, more and more information will flow in, and a more complete picture of the situation will emerge. Many of the preliminary assumptions such as the road quality, the speed that can be driven, distances and usable entry points eventually become certainties. As soon as such information becomes available, the model should be updated based on the information. The frequency of updates could be done multiple times a day if there is new information to be considered.

5.2.2 Multiple ways of finding the best route

In section 5.1.3 it is explained that the model is able to identify all nodes reachable from a certain point in the graph within a certain radius. It's explained that this is based on the travel time it takes to reach other nodes in the graph network. Routing on the quickest route is a straightforward routing option as it chooses a route that prioritizes its route choices on the shortest amount of travel time. This is a useful choice when there is a need to identify the time it takes to reach certain parts of a region. However, using the calculated travel time as the weight factor by determining the shortest path is just one of the routing options.

The model also allows routing by choosing the shortest distance, solely based on the length of the roads and not taking into account road quality or speed. This could come to use when the user has the desire to reduce the number of kilometres driven, or when road quality and speed isn't a factor that needs to be taken into account. Furthermore, it could prove useful when areas need to be reached on foot. Then the distance alone gives sufficient information.

Furthermore, there also is an option of routing on the road capacity, by choosing the route which has the shortest travel time per number of lanes.

Which gives the path that is the quickest while taking mostly high capacity roads. This routing option can be helpful when the user wants to transport high volumes in short times. The capacity of the road is equivalent to the number of lanes on a road. The more lanes on a road, the more vehicles per time unit can travel along the road.

5.2.3 The model as a communication tool

As explained in the previous paragraphs, the model can be used to measure the reachability within a road network and it can adapt to new information that is inserted in the model when the real situation is changing. The most important use of the model is that it functions as a communication tool. The model holds a lot of information and it calculates the reachability while taking all this information into account. In the next chapter, the calculated outcomes of the model are visualised in several ways, and these visualisations can be used to communicate a lot of information efficiently. The model can be used to be the back-end of a dashboard that displays all the visualised information at once, creating an overview of the disaster situation that needs to be monitored. How a dashboard should look like and what needs to be included is described in the next chapter of this research.

5.3 MODEL IMPLEMENTATION

This section elaborates on the implementation process of the model. The construction of the model has been described in section 5.1 and the processes described need to be implemented to create a model. In this research, the model is implemented in Python Programming Language. In this section the implementation in Python is explained, to demonstrate how the model could be built in a chosen programming language. After this, the expected model outcomes are compared to the actual model outcomes for the sake of the verification of the model.

The model is implemented in Python, using the Python package OSMnx, created by Geoff Boeing in 2017 (Boeing, 2017). It's a Python package that allows to retrieve, construct, analyse and visualize road networks imported from OpenStreetMap. OSMnx is built on top of several other Python packages and services, such as geopandas, networkx, matplotlib and the OpenStreetMap API. To maintain a clear structure, the process of the construction of the model in chapter 5.1 is followed and for every step, it is explained how it is implemented in Python. All the installed packages and their versions that have been used are displayed in Table D.1 in Appendix D.

5.3.1 Importing graph network from OpenStreetMap

Importing geographical data from OpenStreetMap

When it's determined for which location the model needs to be built, a query has to be defined to import the geographical data from the desired location from OpenStreetMap. The query to import data of a network could be a bounding box where coordinates are specified, the coordinates of a point with a specified radius around this point, a specific address with a specified radius around this address, a polygon of the network's boundaries, or a place name or list of place names (Boeing, 2017). Within the same query, it's also an option to specify which type of roads need to be included in the imported network, ranging from drivable public streets to including bike paths and private roads

The query is geocoded by Openstreetmap's "Nominatim API", and then a polygon is created based on the geometry of the queried area (Boeing, 2017). For example, when the query consists of the place name "New York City, United States of America", stating the place of interest, then OpenStreetMap's Nominatim API converts the query into a polygon that is associated with the administrative boundaries of New York City. The polygon of the administrative boundary is the output of this process.

Converting geometry data into a multi-directional graph network

The next step is to consult the OpenStreetMap Overpass API to determine what network data needs to be downloaded from OpenStreetMap within the polygon of the specified area. The polygon of the administrative boundaries of a location determines that the road network within these boundaries are to be downloaded. The output of this process is a multi-directional graph network object in Python that represents the road network that lies within the administrative boundaries of the specified location. The network type that is specified determines what level of detail is considered in the multi-directional graph network. The graph object is a 'networkx' graph that holds all kinds of information from OpenStreetMap, such as node and edge attribute information. The information about the nodes and edges are stored in dictionaries that are easily accessible using Python.

Importing geographical data of entry points from OpenStreetMap

The specified entry points that need to be located in in the graph network need to have their coordinates identified. To find the coordinates, a query needs to be configured to consult the OpenStreetMap API. This query should consist of one or more entry point names. When it's one entry point, the query needs to be formulated as the name of the entry point, the place where it's located and the country as one string. When there is more than one entry point specified, it needs to be a list of strings, where each string consists of the name, place and country of the entry point. Each of the queried entry points is then geocoded with the GeoPy Python client by using third-party geocoders such as Google Maps, OpenStreetMap, Bing et cetera (Kumar, 2015). This process returns a set of coordinates for each of the queried entry points.

Locate entry point nodes in the graph network

To locate the entry points in the graph, the distance between the entry point coordinates and the coordinates of the nodes in the graph needs to be calculated using the Haversine formula for all nodes. OSMNX offers a function that gets the nearest node to a specified latitude and longitude point. This function uses the Haversine formula and iterates it over all nodes in the graph object to determine which of the nodes is closest to the coordinate point. This function is used for all specified entry points, returning a Pandas dataframe containing for each entry point an entry point name, the coordinates and the node id of the node that represents the entry point in the graph network. This data frame is stored and can be accessed later on for other processes.

5.3.2 Calculating graph network attributes

Calculating travel time for each edge

Before the travel time is calculated for each edge, the road quality added as an attribute to all of the edges in the graph network and the value is set to 1, indicating that the road is perfectly drivable, assuming there is initially no road quality information available. Then a pandas data frame from the graph's edges containing an origin node id, a destination node id, a street name (if available), a street length and the specified road quality (1), is written to an Excel-file and saved on the computer where the model is operated from. This Excel-file allows the user to adjust the road quality information manually within this Excel-file. When the travel time for each edge is to be calculated, the Excel-file is consulted to get the road quality information that is most up-to-date. This information is then assigned to the edges in the graph network and used in the calculation to get the travel time for an edge. In Python, this calculation is set up by iterating through each of the edges in the graph and first checking whether an edge has an attribute for the maximum allowed speed. If the edge has this attribute, it's then checked whether the maximum allowed speed information is stored as a string or a list, because both appear in the data. When it's a list of two or more speeds, it could be that the speed is variable based on the time of the day for example. If it's a list of speeds, the maximum allowed speed is used in the calculation and the travel time is calculated as described in Appendix E.2. When the maximum allowed speed is available as attribute data for an edge but is a string and not a list, then the string is converted to an integer, and this value is used as the speed in the calculation to find the travel time for the edge. If the maximum allowed speed is not available as attribute information for an edge, the average speed as specified by the user is used to calculate the travel time. Each time the travel time is calculated for an edge, this information is then stored in the dictionary of the edge in the graph.

Calculating flow time for each edge

To calculate the flow time for each edge in Python, an operation is iterated over all edges in the graph, where a new attribute is added to the dictionary in the graph called 'flowtime'. The value of this attribute is calculated by taking the travel time attribute value and dividing this by the number of lanes as specified in the lanes attribute of the edge. The outcome is stored within the graph as attribute information.

Computing edge betweenness centrality

To calculate the edge betweenness centrality in Python, a function from the networkx package is used to create a subset from the edge betweenness centralities. The subset means that the edge betweenness centrality is solely based on the betweenness centrality for the shortest paths between the specified entry points and all other nodes, not of shortest paths between any of the other nodes.

Computing entry point betweenness centrality

To calculate the betweenness centrality of the nodes representing the entry points, a function of the networkx package in Python is used. This function calculates the betweenness centrality for all nodes in the network and creates a dictionary containing all node ids as a key with its corresponding betweenness centrality as a value. The dictionary is used to add this information as attribute information to each of the nodes by iterating over each node.

5.3.3 Determine reachability from entry points to all nodes

To determine the reachability from entry points to all nodes in Python, the routing preference should first be determined. There are three options available to choose as a routing preference, either on travel time, edge length, and flow time. When a routing preference is chosen, a list of desired radii needs to be specified. The radii determine which levels of reachability are to be explored. for the routing options travel time and flow time, the units are in minutes, while for the length, the units are in meters. The set of radii should be specified in a list of any desired length.

To identify which nodes are in a certain radius around each entry point, a subgraph is created for each radius, working in descending order, for each of the entry point nodes. A function of the networkx package is used to create an ego graph, which is an induced subgraph of neighbours centred at one of the entry point nodes within a given radius. When this process is iterated over every radius for each entry point, the result is a set of subgraphs, containing information about which nodes are reachable in a certain time or distance.

5.4 MODEL VERIFICATION

When the model is implemented and working in Python code it's necessary to verify whether the conceptual model is correctly translated into the Python model. This section describes the verification of the model to verify whether the model does what it's supposed to do as specified in the conceptual model.

The verification of the implemented model consists of confirming whether programmed functions are functioning properly. It starts with the first steps of the model according to the process diagram in Figure C.1. It is checked whether the imported location is correct and this can be figured out by creating a plot of the imported graph and comparing the visual image to how it looks in OpenStreetMap or Google Maps. The entry point coordinates are returned by the model are checked by using them as a query in Google Maps and confirming whether they point to the specified entry point. When the model finds the nearest node to any of the entry point coordinates, the coordinates of the returned node are checked in Google Maps as well to confirm whether this node is actually close to the entry point.

For setting the travel time in the model a formula is used that is aimed to let the travel time on an edge be influenced by the road quality and the speed that's allowed. It should behave as such, that the travel time becomes very large when the road quality is nearing zero. To confirm whether the travel time is correctly influenced by both the speed that's allowed and the road quality, the road quality is tested for both 0 and 1 and the travel times are observed.

The flow time attribute in the model is based on the capacity of roads. It should behave in such a way, that when a road has 2 lanes, it would have a flow time that is equal to the travel time divided by the number of lanes, which is 2. To verify whether the setting of the flow time attribute is correctly implemented, an edge with a capacity of 2 lanes is looked up and it's verified whether its travel time attribute is exactly twice as large as its flow time attribute.

The edge betweenness centrality and the node betweenness centrality measures are difficult to verify because the calculations include an extremely high number of shortest routes that are calculated. A way to verify whether the node and the edge betweenness are correctly calculated is to look where the nodes and edges with the largest betweenness centralities are located and to verify whether these nodes and edges are part of something that seems like a relatively important road, such as a highway.

For when the reachability radii are calculated from the specified entry points, it needs to be verified whether the largest radius produces the largest area of reachability and that the smaller radii produce smaller reachability areas subsequently. This can be confirmed by identifying the size of the reachability subgraphs that are created in this process. Also, the correctness of the found reachability is compared to what could be found in Google Maps, when measuring the travel time or distance between two points in a network.

All these model expectations are included in Table F.1 that's in Appendix F, where also the verification status of the expectation is mentioned. All the expectations of the model have been verified and are positively confirmed. This leads to the conclusion that the model as constructed and implemented behaves as it is programmed to.

5.5 MODEL SUMMARY

The model is constructed and implemented in Python and it can be used to improve situational awareness in sudden-onset disasters in the very beginning of the response phase. The model includes all sorts of data and several metrics that are relevant for this research are calculated using the data of the model. When the model is implemented and initiated to use during a sudden-onset disaster, the user is prompted to specify a location and one or more entry point locations. This information determines the construction of the graph and from where the reachability needs to be calculated. Then the model requires input for the average speed that might be driven in the area. This average speed is applied for all road segments for which the lawful speed limit is unknown. The model also offers the option to adjust the road quality information of the road segments in the network. By default all road qualities are set to 1, assuming that all roads are in ideal condition.

This information can be adjusted and then the model takes the adjustments into account. Then the model requires a specification of the routing option that is desired. There are three routing options available, routing by minimizing travel time, routing by minimizing travel distance and routing by maximizing road capacity while minimizing travel time. Then the model requires to specify a list of radii for which the network's reachability should be calculated. These radii are in either minutes or meters, depending on the routing option that is specified. Following these steps will initialize the first state of the model.

When the model is set up, new incoming information can be inserted into the model. There could be situations where information becomes available about one part of a region that is flooded and therefore the roads are completely impassable. When inserting this into the model, the road quality of the roads that are flooded are to be set on 0. With this new information, the reachability can be recalculated, taking the impassable roads into consideration, which will yield insights into which areas have become less reachable due to the loss of several roads. Another situation could be that an airport that is used as a logistical hub becomes unreliable due to a landslide for example. Then this airport location could be omitted from the model and then the reachability is recalculated taking into account that there is one entry point fewer in the network, leading to a lower reachability of the area. The different inputs the model can be given and the adjustments that can be made as a disaster situation develops are described in Table G.1 located in Appendix G

All the information that collected with the model is visualised in a variety of ways in the next chapter. By visualising the information that the model yields, the model can function as a communication tool for aid workers. When the visualised information is combined into a dashboard it could be used to monitor the road network in a disaster-struck area to improve situational awareness. Especially when the dashboard shows the changes over time, leading to more effective disaster response. The model implementation can be found in a Jupyter Notebook on Github, which can be reached via the URL:
https://github.com/vipalkema/MSc-Thesis-MakingReachabilityMaps.

6 VISUALISING THE OUTCOMES OF THE REACHABILITY MODEL

"Numbers have an important story to tell. They rely on you to give them a clear and convincing voice"

Stephen Few

The construction, use and implementation of the model in Python are described in the previous chapter. While how the model is used to create communicative visualisations and how the visualisations are implemented is elaborated on in this chapter.

Three types of visualisations are used in this research and the three are combined at the end of this chapter. The first visualisation is one where the reachability of different parts of a region by aid workers from several entry points is illustrated. This visualisation shows how long or how much distance it approximately takes to reach any location in the region. The second visualisation is one where the road quality and the road criticality is visualised. With such a visualisation it can be interpreted where there are constraints in the network, and how important the roads in the network are. The third visualisation that is elaborated on are plots of metadata of the graph network. Each time the model is run when data has changed, the metadata of the model will also be different. Therefore bar charts of metadata such as entry point betweenness centrality, edge betweenness centrality and node betweenness centrality offer valuable information. Ultimately, all produced visualisations are combined together into a dashboard that offers a complete overview of all the visualisations that allow monitoring of the sudden-onset disaster.

In this chapter, the implementation of each of the three types of visualisations are described and an example is given for a specified location. The location that is used to demonstrate the visualisations is Rotterdam, the second city of the Netherlands and the entry points that are selected are three locations in Rotterdam; Rotterdam Airport (the airport of Rotterdam), Rotterdam Central Station, and Zuidplein Rotterdam. The last two are not actual entry points, but they will act like they are for the demonstration. Rotterdam is selected as a location because it's not a very large city and it has a lot of information available in OpenStreetMap. Rotterdam and the specified 'entry points' will be used as input queries. All road qualities are set to 1 and the average speed that can be driven is 30 kilometres per hour. In Appendix H a thorough description of how each visualisation is implemented in Python is offered.

6.1 VISUALISING REACHABILITY OF THE REGION

The goal of visualising the reachability of a region is to analyse the data that is available. The reachability can be illustrated in a meaningful way by using the set of radii as described in the conclusion of the previous chapter. The last step of the implementation process of the previous chapter will be partly repeated to create the visualisations. For the visualisation of the reachability of an area, three routing options can be chosen; measuring reachability in travel time, distance and a combination of road capacity and travel time.

6.1.1 Visualising reachability measured in travel time

When measuring reachability by travel time, the radii need to be specified in minutes of travel time. For Rotterdam, the radii [0, 2, 4, 8, 12, 15, 18, 30] are suitable, because it's assumed that within 30 minutes, a significant part of the city should be reachable in normal conditions.

When these inputs are used in the model, the visualisation as illustrated in Figure 6.1 can be created. A more thorough explanation of how the visualisation is implemented in Python can be found in Appendix H.1.

In this figure, the specified entry point locations can easily be found by looking at the blue dots. Furthermore, the colour bar on the right side gives guides how the figure should be read. The darker the area becomes, the longer it takes to reach the area from one of the blue dots. When this visualisation is used in a sudden-onset disaster, and the blue dots would represent the entry points from which aid workers will come in. The red dots represent the most important junctions of the network and the red coloured edges represent the most important roads in the network. The importance is measured in betweenness centrality, which is the number of shortest paths that go across these junctions and roads. It can be observed that one particular road segment is very important in the network.

6.1.2 Visualising reachability measured in distance

When there is an interest in what the reachability in an area is when only focusing on distances and not on the time it takes to travel, the route option can be set to focus on the length of the edges. When using the length as the weight of the edges, the set of radii has to be chosen differently as well, because it uses metres as the unit. The set of radii chosen for demonstration is [200, 500, 1000, 2000, 4000, 6000, 8000, 10000], which are values in metres. The largest radius will cover most of the city and when the model is run, it will give insight into what the distance is of areas towards the specified entry points, considering the road network.

Using these inputs in the model will yield a visualisation as illustrated in Figure 6.2. The implementation of this illustration is done in the same way as the previous visualisation and can be consulted in Appendix H.1. It can be seen from the figure, that most of the city is covered within the 10 kilometre radius and that only one part of the city is farther away from any of the entry points. It's also visible what the relative reach of each entry point is. The most upper blue dot in the figure is Rotterdam Airport, and

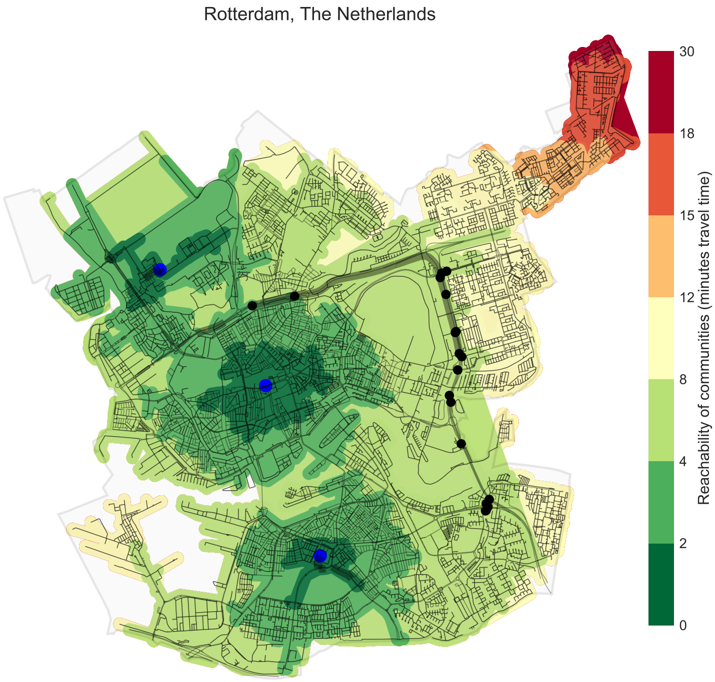

Figure 6.1: Visualisation of reachability in Rotterdam based on travel time. The colours indicate the reachability within a certain radius, the black dots represent the most critical junctions, the blue dots represent the entry points and the thick black lines indicate the most critical roads.

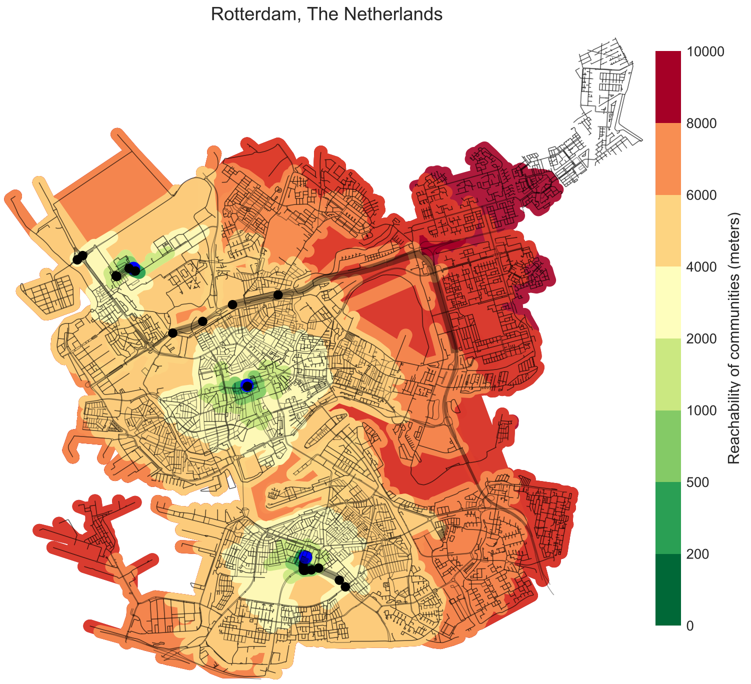

Figure 6.2: Visualisation of reachability in Rotterdam based on road length. The colours indicate the reachability within a certain radius, the black dots represent the most critical junctions, the blue dots represent the entry points and the thick black lines indicate the most critical roads.

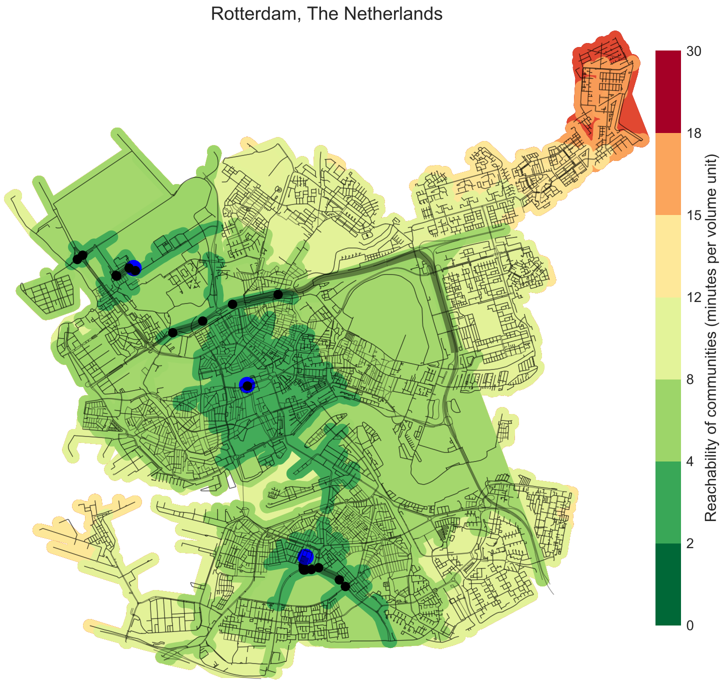

Figure 6.3: Visualisation of reachability in Rotterdam based on travel time and road capacity. The colours indicate the reachability within a certain radius, the black dots represent the most critical junctions, the blue dots represent the entry points and the thick black lines indicate the most critical roads.

has a lower reach than the other two blue dots, looking at the size of the lighter coloured radii.

6.1.3 Visualising reachability measured in travel time and road capacity

When calculating the reachability using the third routing option basing it on the flow time, which is the volume per time unit, another visualisation is produced. The flow time can be useful when there is an interest in how long it takes to transport vehicles taking the capacity of the road into consideration, as more capacity allows more vehicles at a time. There the flow time is used as the weight for the edges and the radii are set on [0, 2, 4, 8, 12, 15, 18, 30], which is in minutes per volume unit. These inputs will yield the visualisation as illustrated in Figure 6.3

From this figure, it becomes clear what the reachability of areas are in terms of the capacity of the roads, and it shows a somewhat similar result to Figure 6.1. However, Figure 6.3 seems to have a larger reachability, especially in the areas close to the highways, which can be expected, because the highways have a higher capacity, and a higher speed limit, making the areas around it more reachable in a shorter time. Additionally, the highway is also indicated as the most important road measured by edge betweenness with the red lines and dots in the figure.

6.2 VISUALISING ROAD QUALITY AND CRITICALITY

The next visualisation visualises the road quality of the roads in the network and the criticality of the roads in the network. The road quality is manually inserted into the model, and the criticality of a road is represented by the edge betweenness centrality of a road that is based on the number of shortest paths between the entry points and any other node that cross an edge.

6.2.1 Visualising road characteristics in ideal conditions

The road quality is on a scale of 0 to 1 and the colour scale the represents the road quality value is from red to yellow to green. Red represents a road quality of 0, when a road is completely impassable, while a green road represents a road in ideal condition. The width of a road represents the relative edge betweenness centrality value. The more important a road is for aid workers coming from either one of the specified entry points to reach any point in the network, the thicker the road is drawn in the visualisation. The very thin drawn edges are edges of low criticality, and thus a low impact on the reachability within the network as a whole. Also, in this figure, the red dots indicate the junctions in the network that are the most critical based on node betweenness centrality. When it's observed that roads close to this junction are

In ideal conditions, all roads have a quality of 1 and the edge betweenness is calculated accordingly. Visualising the road network with these inputs leads to a result as shown in Figure 6.4.

It can indeed be seen that all roads in the network are green and that the legend indicates that this means that the road quality is 1.0. Also, a difference in the thickness of edges can be observed. It's clear that roads that are thoroughfares are much thicker than the roads that connect residential areas.

6.2.2 Visualising road characteristics when roads are broken

In the case that the road conditions are not ideal, the visualisation should show a different figure. To observe whether the figure is able to show broken roads or roads with worse quality, the road qualities that serve as input for the model are adjusted. The road quality of quite some edges are set to 0, 0.2, 0.5, 0.7 or they remain at 1. This change should be visible in the visualisation.

In Figure 6.5, a network can be seen where several roads are red, orange, yellow or light green. This indicates the roads that have been manually 'broken'. This model and this visualisation can be used in reality to quickly create an overview of the conditions of the network and how important some of the roads are. This gives additional insights into the reachability

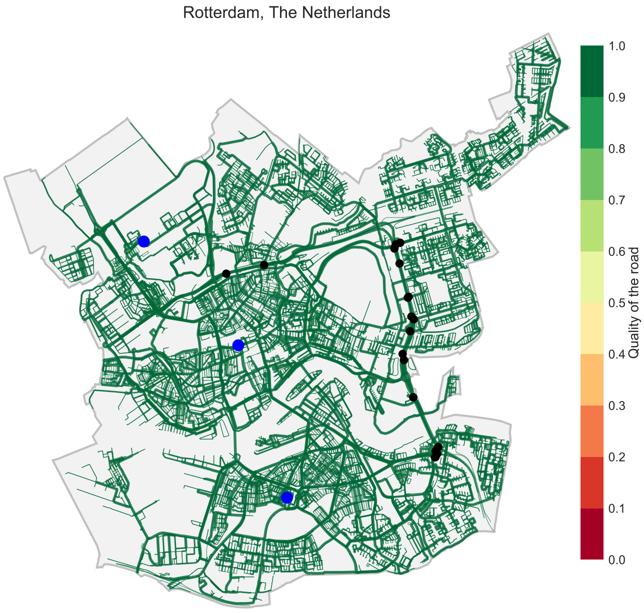

Figure 6.4: Visualisation of the road quality and the road criticality in ideal conditions

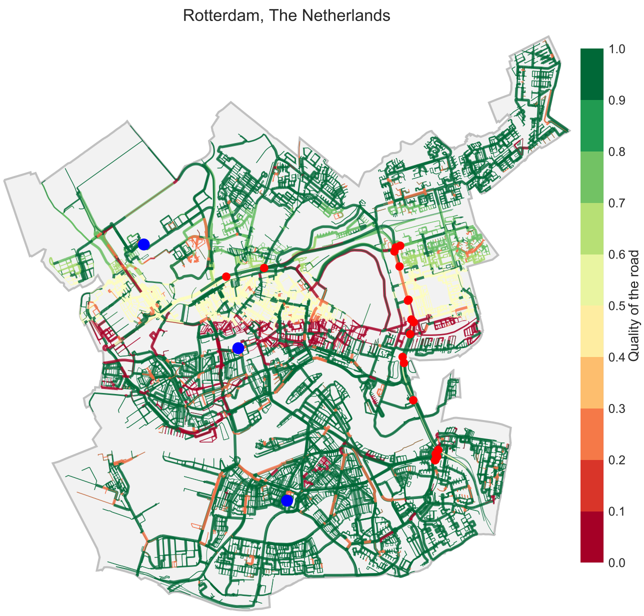

Figure 6.5: Visualisation of the road quality and the road criticality including broken roads

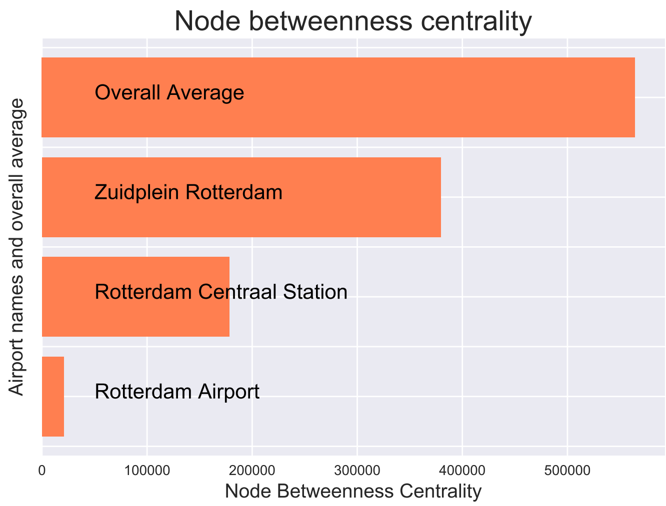

Figure 6.6: Betweenness centrality of the entry points compared to the overall average betweenness centrality

visualisation, as the road quality visualisation could show that perhaps the condition of a certain road causes the reachability of a certain area to be particularly low.

6.3 VISUALISING META INFORMATION OF THE ROAD NETWORK

The graph network consists of all kinds of information that is relevant for understanding the system as a whole. The betweenness centrality attributes that have been calculated in the model can be shown in visualisations that are demonstrated in this section.

6.3.1 Entry point betweenness centrality

The specified entry points have an important role in the network, as they function as a logistical hub during sudden-onset disasters and are the starting point of many relief efforts. It's relevant to know what the structural importance of an entry point is, mainly because this indicates how well connected the entry point is to other nodes in the network. The structural importance of any node is measured by the betweenness centrality. In Figure 6.6, the betweenness centrality of the specified entry points is plotted in a histogram and compared to the overall average betweenness centralities of the nodes in the network.

From the figure, it can be seen that all three of the specified entry points have a betweenness centrality that is below average, and that especially Rotterdam Airport has a particularly low betweenness centrality. This indicates that the entry points are not particularly well connected to other nodes in the network. When the changes occur in the network during the response phase of a disaster, the betweenness centrality of these entry points will also

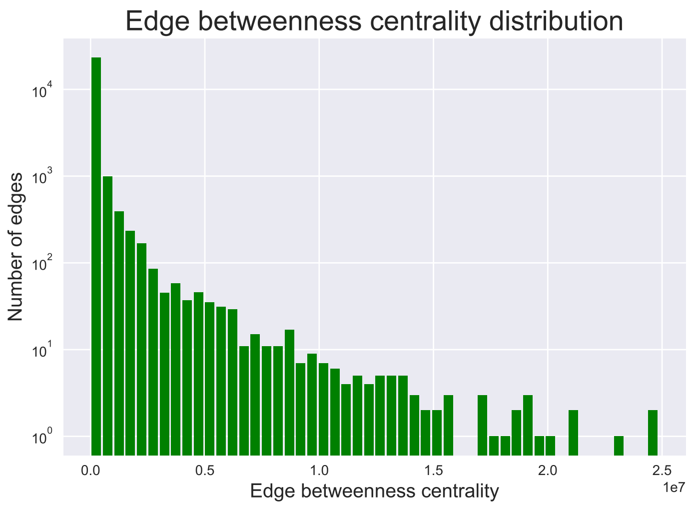

Figure 6.7: Distribution of edge betweenness centrality over the edges in the network

change and could be monitored via a visualisation such as Figure 6.6. This visualisation could also help to identify which entry point is more useful. It could be decided by looking at this figure, that Zuidplein, Rotterdam is a more suitable entry point than Rotterdam Airport for setting up a logistical hub, based on the structural importance of the entry points.

6.3.2 Edge betweenness centrality

There are different types of roads in the network with different levels of importance. There are highway roads that connect various parts of Rotterdam, but there are also narrow roads that have a dead-end in some residential area. In Figure 6.4 and 6.5, the edge betweenness has already been drawn on the map to identify which roads have what level of edge betweenness. The level of edge betweenness tells something about how critical a road is to the network and in this research especially how important it is for connecting the entry points with the rest of the network. In Figure 6.7, an overview is given of the distribution of edge betweenness centrality in the network. A histogram is used to provide information about how many edges there are for different levels of edge betweenness centrality. For aid workers, the most important information that can be interpreted from this plot is the number of edges that have very high betweenness centrality. This information can be used to determine how many black dots should be shown on the reachability map to indicate the most critical roads. In Figure 6.7, it shows that there are 2 edges with a betweenness centrality of $2.7 * 10^7$, and 15 edges with a betweenness centrality between $1.7 * 10^7$ and $2.3 * 10^7$. So, it may be determined based on this information that the approximately 20 edges with the highest betweenness centrality should be displayed on the reachability map with black thick lines.

In Figure 6.7, it can be seen that there is a high number of nodes that have an edge betweenness centrality of 0. More than 10,000 nodes barely seem to have importance for connecting the entry points to the rest of the net-

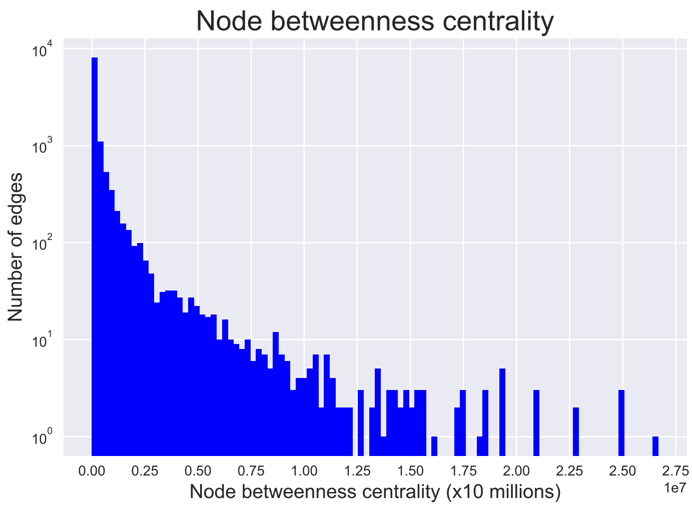

Figure 6.8: Distribution of the node betweenness centrality over the nodes in the network

work. And there are a few nodes that have an extremely high importance in the network. This graph gives additional information to Figure 6.4 and Figure 6.5 by giving a more complete view of the road criticality. When the plot shows that there is a high number of edges with a high betweenness centrality, then the road network is vulnerable to problems, because this means that the reachability within the network relies heavily on certain roads. When such roads become damaged, the whole network suffers an impact on the reachability. Therefore, it's desired to observe a high number of edges with a very low betweenness centrality and a low number of edges with a high betweenness centrality.

6.3.3 Node betweenness centrality

The betweenness centrality of a node indicates how structurally important a node is in the network for connecting all pairs of nodes in the network. When more shortest paths between any pair of nodes go through a particular node, the higher the betweenness centrality of this node becomes.

Figure 6.8 shows how many nodes have what level of node betweenness centrality. Similar to Figure 6.7, there is a high number of nodes that have a very low node betweenness centrality. There also a few dozen nodes that have extremely high node betweenness centralities. There is one that has more than 25 million shortest paths going through itself. In Figure 6.8, it shows that there is one node with a betweenness centrality of $2.7 * 10^7$, and 15 nodes with a betweenness centrality between $1.9 * 10^7$ and $2.5 * 10^7$. So, it may be determined based on this information that the approximately 20 edges with the highest betweenness centrality should be displayed on the reachability map with black dots.

6.4 COMMUNICATING OUTPUTS TO AID WORKERS

When the previously generated visualisations are combined in a dashboard where all visualisations are visible at once, this could be useful for aid workers as they can observe the developments of the road network and thus the reachability in the network. Figure 6.9 illustrates how such a dashboard could look like. It shows the maps of the reachability and road quality on top being the most important information. Below the maps, there are three plots that show information about the network in general and about the structural importance of the entry points. To the right, there is a side-bar that indicates relevant information of the network when monitoring a sudden-onset disaster. It shows the date and the location, also what kind of routing type is selected. This is important to know when interpreting the reachability map. It also shows the time step, each time the map gets updated with new information, the time step advances one step. Lastly, the side-bar shows the number of roads that are still functioning and the number of roads that are broken.

To evaluate whether the designed artefact that consists of a model and visualisation output works in reality, it's important to conduct test-cases to validate whether the model if feasible both technically and practically. The evaluation of the designed artefact is elaborated on by conducting two case-studies. The implementation of the visualisations can be found in a Jupyter Notebook on Github, which can be reached via the URL:
https://github.com/vipalkema/MSc-Thesis-MakingReachabilityMaps.

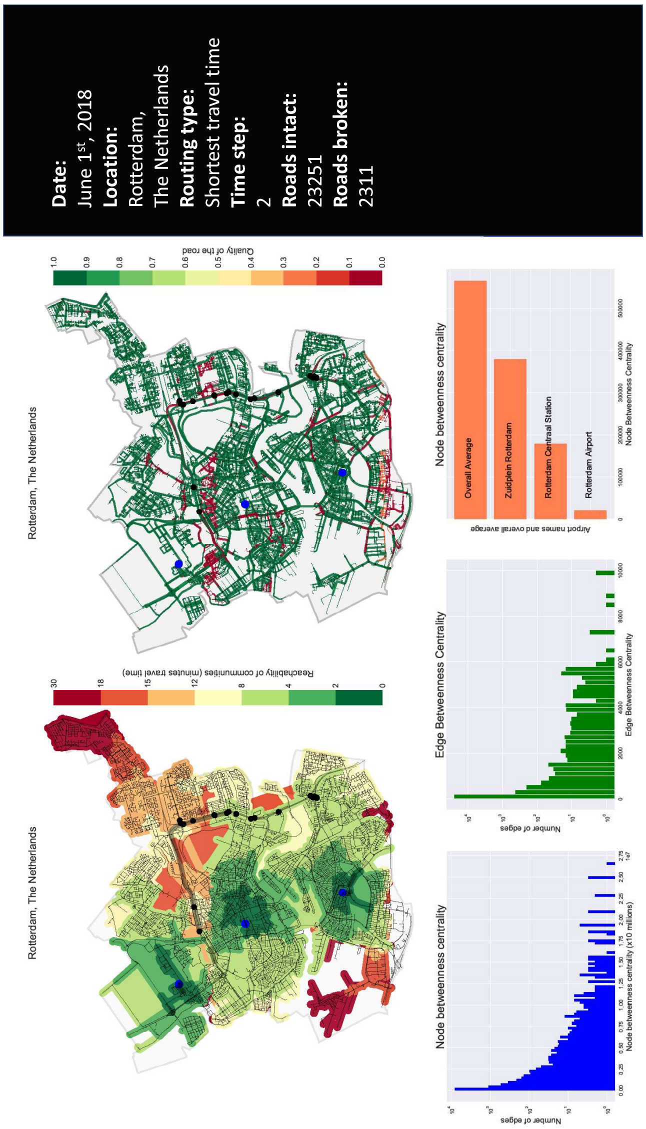

Figure 6.9: Dashboard including all visualisations in one overview. Upper left is the reachability map. Upper middle is the road quality map. Right side-bar is meta-information. Lower left plot is the node betweenness centrality distribution in the graph. Lower middle plot is the edge betweenness centrality distribution in the graph, and the lower right plot is the entry point betweenness centrality compared to the overall average.

7 EVALUATING THE REACHABILITY MODEL

"The true method of knowledge is experiment"

William Blake

After finishing the development stage of the research in the previous chapters, the research has now arrived at the evaluation stage according to the framework of Hevner et al. (2004) as a part of the design cycle. The designed reachability model reconstructs a road network of a specified region which carries information that can be visualised into reachability maps, road quality maps and several plots that give information about the network's characteristics. The visualisations can be put together on a dashboard to create an overview of the disaster situation.

Whether the reachability model is feasible to use during a sudden-onset disaster is yet unknown. Therefore this chapter focuses on evaluating the reachability model by applying it to two real situations that happened in the past and conducting semi-structured interviews with field experts. First, the technical feasibility and the practical feasibility of the reachability model are evaluated by applying the reachability model to the disaster situation of Hurricane Irma in September 2017, that destroyed large parts of Sint Maarten's infrastructure and causes several deaths and left many injured. Second, the technical and practical feasibility of the reachability model is evaluated by applying the reachability model to the Papua New Guinea earthquake that occurred on February 26^{th}, 2018 in Hela Province. The area involved in the Papua New Guinea earthquake is much larger than Sint Maarten and also the road network is quite sparse, with not a lot of information available. This case is expected to be a more difficult but more realistic situation compared to Sint Maarten because in practice there is no guarantee that a region that is struck by a disaster has available data and information systems in place to support situational awareness. After the two case-studies, the results of the model are demonstrated to two field experts during an interview to evaluate the practical feasibility of the reachability model.

For both of the case-studies, the first step is to elaborate on what happened during both of the disasters and what area had been struck by the impact of the disaster. Then the model is configured for the region affected by the disaster. The model is initially configured on the road network of the region as-is, without taking any disaster into consideration. After this, the visualisations combined on a dashboard is produced for the default state of the network. Then the information that is available about where the disaster struck, what damage it did to which segments in the network and what entry points have been affected, is included within the model, to reconstruct the disaster context. Then the visualisation dashboard is produced again and compared to the default state. Furthermore, the reachability visualisation laid next to available vulnerability and impact assessments, to experiment how the reachability model can be used when information about affected people or destroyed buildings is used.

7.1 CASE-STUDY SINT MAARTEN

On Wednesday, September 6^{th}, hurricane Irma passed over Sint Maarten with winds beyond 300 kilometres per hour, causing lots of damage on the island. According to the Red Cross, 90% of the buildings on Sint Maarten were damaged by Irma, from which a third was completely destroyed. Also, the harbour and the airport had suffered heavy damages, making it difficult to reach the island by relief organisations.

The case-study on hurricane Irma on Sint Maarten starts with the configuration of the model where all roads are intact on the island without adding any information regarding the destruction the infrastructure has suffered. When the model is configured as-is, the visualisation dashboard of this situation is created, to create an overview of the reachability in the as-is situation. Then based on the reports of the disaster, the destruction of the infrastructure is taken into consideration in the model, by updating the model information, including destroyed roads and airports or harbours. Then a new visualisation dashboard is created that identifies the reachability on Sint Maarten in the disaster context. Both dashboards are compared to see what is changed in the reachability as a result of the damage that has been done to the infrastructure. Thereafter, the visualisations of the model outcomes are juxtaposed to other assessments, such as vulnerability maps of Sint Maarten and impact assessment maps. In the comparison, it's explored whether there are relevant conclusions that could be drawn by combining the various assessments. To conclude the section, both the technical and practical feasibility of the model is evaluated, based on the usefulness of the model for applying it to this case.

7.1.1 Configuring model as-is

To configure the model for Sint Maarten, the query for Sint Maarten, the Netherlands, is inserted into the model and the entry points from which potential humanitarian aid could come in is set on the international airport of Sint Maarten, Princess Juliana International Airport, and the cruise port in Great Bay. It's assumed that all road qualities are optimal and that the average speed that can be driven is a roughly estimated 30 kilometres per hour. The radii for which the reachability is measured in minutes are [5, 10, 12, 15, 18, 20, 25, 30, 35, 45, 60], assuming that everything should be reachable on Sint Maarten within an hour.

7.1.2 Visualisation dashboard road network as-is

The visualisations are run in the model based on the previously determined specifications. The visualisations include the reachability map, the road quality map, the node betweenness centrality plot, the edge betweenness centrality plot, and a plot of the node betweenness centrality of the

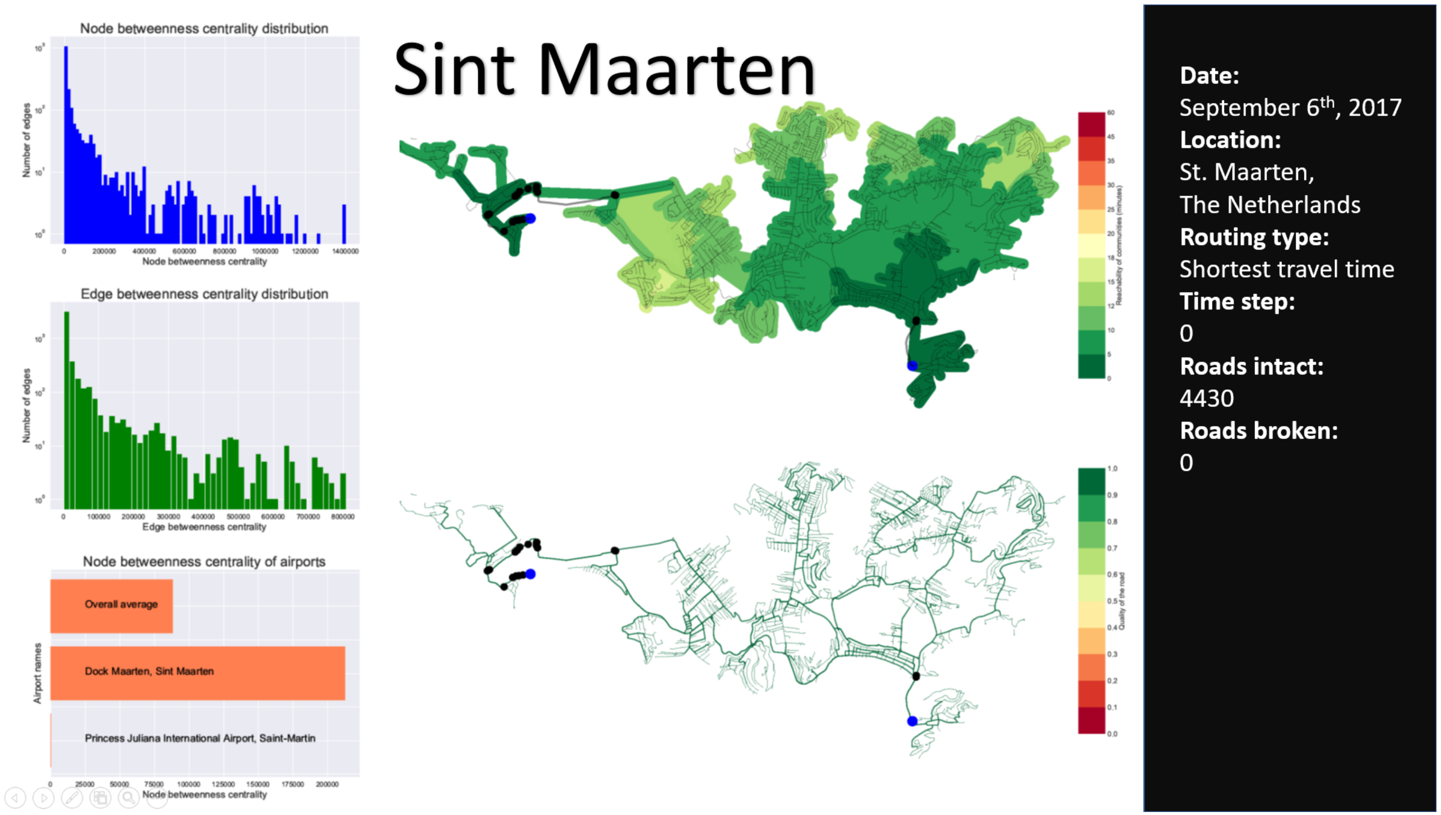

Figure 7.1: Visualisation Dashboard of Sint Maarten in a pre-disaster context. Upper left: shows how the node betweenness centrality is distributed over the nodes in the network. Middle left: shows how the edge betweenness centrality is distributed over all the roads in the network. Lower left: compare the betweenness centralities from the airport, the harbour and the overall average in the network. Upper middle: Shows the reachability of Sint Maarten in minutes. The blue dots are the airport and the harbour of Sint Maarten, the black dots are the most important road junctions that connect the region with the entry points, the wider black edges are the most important road segments that connect the region with the entry points. Lower middle: shows an overview of the road quality, green means the quality is good, red means the road is not working. Blue and black dots have the same meaning as in the upper middle figure. Right sidebar: metadata of the road network and context.

airport and the harbour. In Figure 7.1, a dashboard is illustrated where the visualisations are combined into an overview, including a sidebar with the context and model information. The visualisations are those that have been explained in Chapter 7 and the sidebar shows information about the date on which the model is run, which is the date when the hurricane Irma struck, the location for which the model is run, the routing type that is chosen, the time step in the process and the number of roads that are either functioning or broken.

The visualisation dashboard reveals information about Sint Maarten on different aspects. The plot located on the upper left side of Figure 7.1, displays the node betweenness centrality distribution of the nodes in the network. This basically illustrates what number of nodes are part of a number of shortest routes. It can be deducted from the plot that more than 1000 nodes have a node betweenness centrality of 0, meaning that they are not part of any shortest route within the network. The higher the node betweenness centrality of a node, the more critical this node becomes for connecting different segments within the network. Therefore it's desired to see a higher number of low node betweenness centralities than high node betweenness centralities. In the case of Sint Maarten, it can be seen that the network has a relatively high number of dependency points, looking at how the distribution has quite a large distribution on the right side of the plot. This makes the network relatively fragile.

The plot located on the middle left side has a similar meaning to the previous plot, but then for the edges instead of the nodes. It shows the distribution of the edge betweenness centrality. Also here it applies that a network's distribution is leaning to the left and has a small right side of the plot. However, also here it can be seen that there is a quite large part of the edges with a high betweenness centrality, confirming that the network is relatively fragile.

The plot on the lower left side displays a comparison between the betweenness centrality of the airport, the harbour and the overall average within the network. This creates insight into how relatively well-connected the airport and the harbour are with the network. It can be deducted from the plot that Princess Juliana International Airport is not well-connected to the network, as no shortest route from any point in the network to any other point in the network goes past the airport. Contrarily, the harbour, Dock Maarten, seems very well-connected with the network. It has a betweenness centrality that rises higher than the average. Based on this information, it can be interpreted that it's easier to reach people from the harbour than from the airport.

The map in the upper middle shows the reachability within the network measured from both the airport and the harbour. Guided by the legend, it can be deducted from the map that the whole island can be reached within 15 minutes. It can also be seen that the harbour (which is indicated by the right-most blue dot), has a larger reach than the airport has. The map also shows with black dots that there are many critical junctions close to the airport, making this a relatively fragile location to reach people from. There are also a few critical junctions close to the harbour. If these critical junctions or adjacent roads become damaged, this will have a significant impact on the reachability within the network.

The map in the lower middle shows the road quality in the network and the criticality of the roads. The road quality is indicated by a colour, and all roads are green, as the model is configured with roads in ideal conditions. The width of the road indicates the importance of the road for connecting different locations within the network. This way, the more important roads like highways can be easily identified. Similar to the reachability map, here the airport and the harbour are indicated with a blue dot and the black dots indicate the most critical junctions in the network.

The black side-bar shows information about the context and the model. It gives a date, indicating for what day the model is run and it indicates for which location the network is visualised. Furthermore, it displays the routing type for which the reachability is mapped and what the time step is. The time step could be relevant when multiple moments are mapped consequently. Lastly, the side-bar displays how many roads are intact and broken. In this case, all roads are functioning well.

The dashboard as a whole supports situational awareness because it can be interpreted what the state of the network is and how critical some segments of the network are. Furthermore, it can be derived that the whole of Sint Maarten is reachable within 15 minutes in this context. This level of reachability is mostly because of the good position of the harbour.

7.1.3 Reconstructing disaster context

Hurricane Irma caused destruction all over Sint Maarten, many buildings were destroyed and people lost their homes. In Figure I.1 the assessment on the building damage on Sint Maarten as of September 12^{th} is displayed. This map indicates where most of the damage was done by the hurricane to buildings and for this research, it's assumed that the building damage can function as an indicator for the damage to the roads, as there is no specific road quality information available from right after the disaster. The roads close to some of the highest densities of destroyed buildings on the assessment map are considered to be non-functional in the disaster context. Roads that are nearby less dense areas of destroyed buildings get a road quality of 0.2 or 0.5 depending on the destruction density that's indicated on the map of Figure I.1. It's assumed that debris from the destroyed buildings is on the road and may obstruct the effective use of the road, therefore the road qualities are adjusted. All other road qualities are set on 0.85, to reproduce a situation where all roads are somewhat affected by the debris from the hurricane.

Furthermore, according to reports from the Red Cross such as Rode Kruis Nederland (2017), both the harbour and the airport have been heavily damaged by the storm. Only the airport is somewhat recovered several days after the disaster. This information is included in the model by deleting the harbour of Sint Maarten as an access point and only including the airport as an access point onto the island.

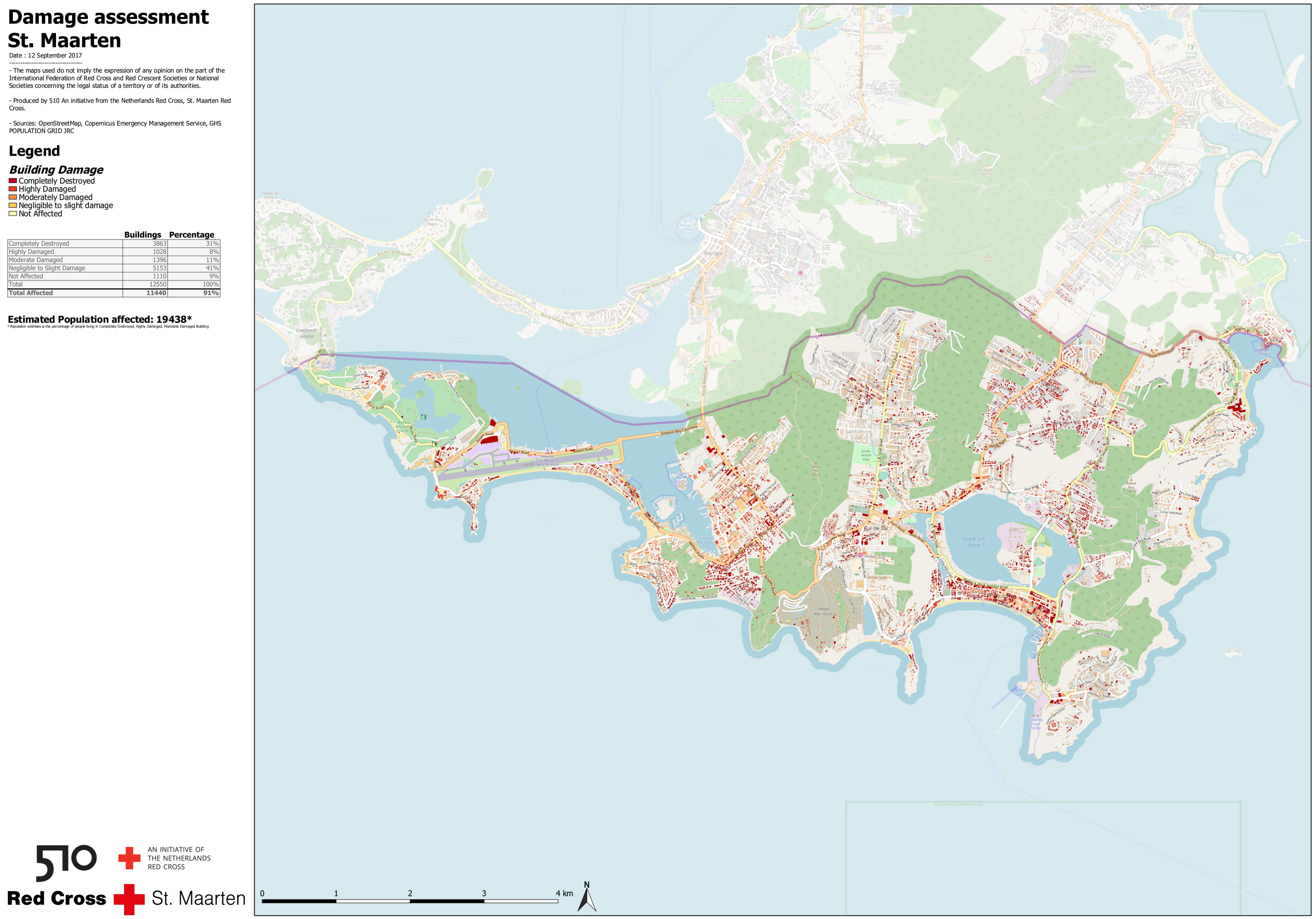

Figure 7.2: Damage assessment of Sint Maarten as of September 12^{th} as a consequence of hurricane Irma(510 Red Cross, 2017a).

7.1.4 Visualisation dashboard of disaster reconstruction

The output of the reachability model for the reconstructed disaster situation is illustrated in Figure 7.3. What can be seen is that the harbour of Sint Maarten isn't functioning as an entry point any more. Only Princess Juliana International airport is remaining as an entry point. Furthermore, there are several roads that are not functioning any more and they're indicated with red. All the other roads are a lighter green, indicating that they're still functioning, but they have suffered damage, making traffic on these roads more difficult.

The reachability map in the upper right of Figure 7.3 shows a whole different reachability than in the pre-disaster situation as displayed in Figure 7.1. The omission of the harbour of Sint Maarten as an entry point onto the island impacts the reachability on the island. Locations close to where the harbour is are now harder to reach. The area directly around the airport is quickly reachable in around 10-12 minutes. While more on the east side of the country, the travel time increases to 45-60 minutes. Some parts in the north-east are not reachable within the measured time radii, meaning that those areas take more than 60 minutes to travel to. In this reachability map, the road that starts at the airport and connects it to the rest of the island is indicated as the most critical road of the network, which could be expected. This means that this road is important to protect, as its functioning is of crucial importance for the reachability of victims.

7.1.5 Combining model outcomes with humanitarian parameters

The reachability dashboard of Sint Maarten in the disaster context is combined with humanitarian parameters that are derived from impact assessments to analyse how the model could be used when dealing with actual information about affected people or buildings. In Appendix I, two assessment maps of hurricane Irma and the devastation on Sint Maarten are displayed. Figure I.1 shows the damage after hurricane Irma per sub-area, from which it can be interpreted what areas have the highest urgency for relief (510 Red Cross, 2017a). Figure I.2 shows the wind impacts on Sint Maarten by hurricane Irma. This gives a more detailed view of the damage on the island because it also differentiates between different levels of destruction (Pacific Disaster Center, 2017). These impact assessments usually take a long time to be created and are often only available after a week or more. The reachability model has the advantage that it can become available directly as a disaster strikes. The impact assessments from Appendix I are used to analyse how the reachability model can be used in combination with information about victims. The information about victims and destroyed buildings are collected from the start of the response phase. However, it's not all centralized in a map such as the assessments in Appendix I.
The overview of the damage per sub-area of Sint Maarten as displayed in Figure I.1 indicates which parts of Sint Maarten have been impacted the most. Both in relative numbers as absolute numbers. The sub-area where an almost full circle with the number 525 in it is displayed, is an area where the hurricane destroyed nearly everything. However, this sub-area is not the area where most buildings have been damaged. That would be the circle with 991 in it, in the upper sub-area third segment from the right. In Figure I.2 the highest density of completely destroyed buildings (red spots)

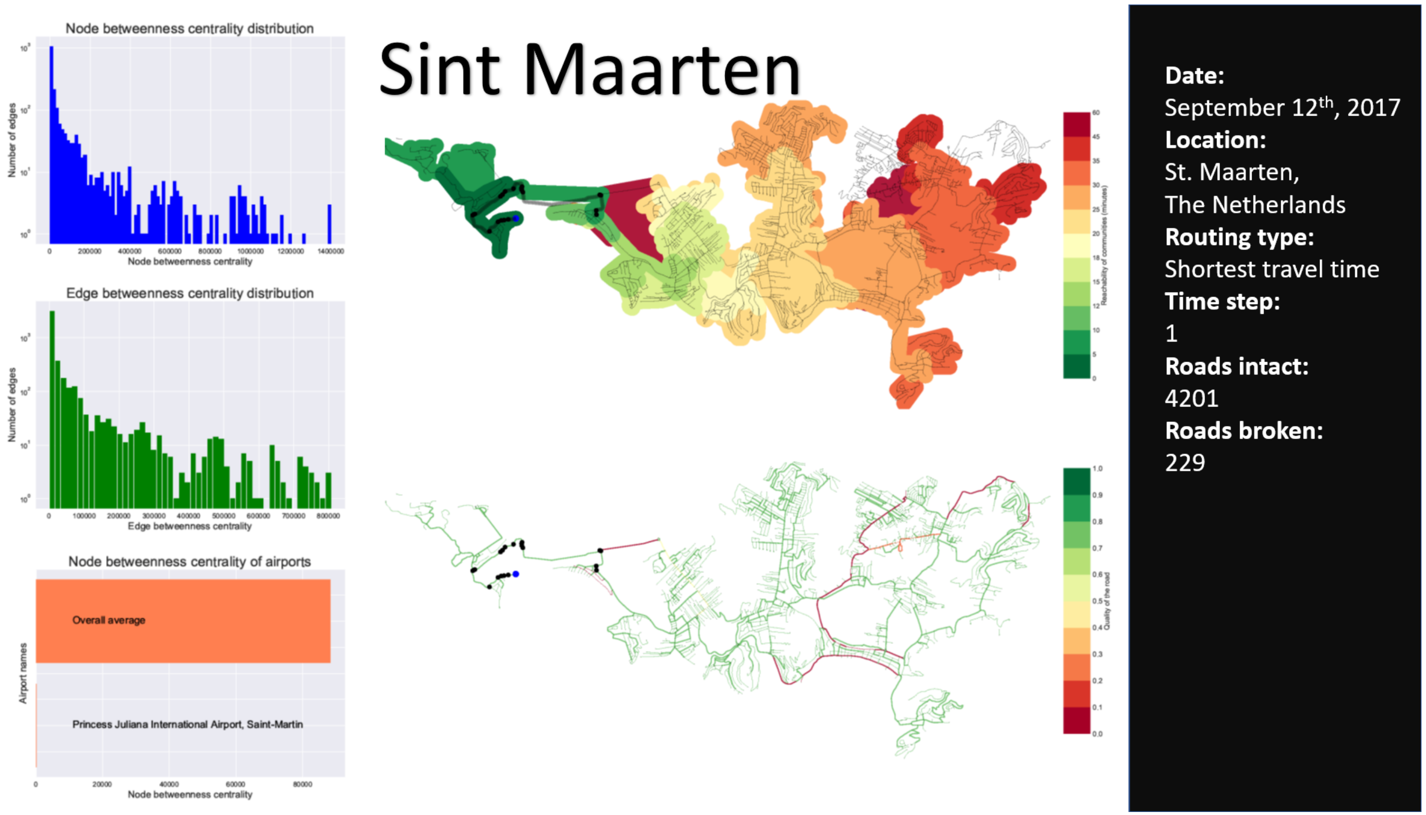

Figure 7.3: Visualisation Dashboard of Sint Maarten in a post-disaster context. Upper left: shows how the node betweenness centrality is distributed over the nodes in the network. Middle left: shows how the edge betweenness centrality is distributed over all the roads in the network. Lower left: compare the betweenness centralities from the airport, the harbour and the overall average in the network. Upper middle: Shows the reachability of Sint Maarten in minutes. The blue dot is the airport of Sint Maarten, the black dots are the most important road junctions that connect the region with the entry points, the wider black edges are the most important road segments that connect the region with the entry points. Lower middle: shows an overview of the road quality, green means the quality is good, red means the road is not working. Blue and black dots have the same meaning as in the upper middle figure. Right sidebar: metadata of the road network and context.

can be found in the same area as the sub-area with the highest absolute number of destroyed buildings in Figure I.1. The sub-area with the highest relative number of destroyed buildings and the sub-area with the highest absolute number of buildings are compared to the reachability dashboard as displayed in Figure 7.3.

The sub-area with the highest relative number of destroyed buildings is quite reachable according to the reachability dashboard. This area is relatively close to the airport and is reachable within 15-18 minutes from the airport by aid workers. This is positive for the affected people that live in this sub-area that has suffered a lot of impact from the hurricane. The sub-area where the highest absolute number of destroyed buildings is indicated is much harder to reach from the airport. This area has a travel time ranging from 35 minutes to more than an hour. This sub-area is one of the least reachable areas on Sint Maarten. When aid workers come across such a situation, where the area that probably needs to most help is also the area that is the hardest to reach, this could have dire consequences for the victims. Decision-making based on such information could involve a higher priority for preparing the harbour to be functional again for aid workers to use.

The combination of the reachability dashboard of Sint Maarten and information about victims and destroyed buildings gives additional information that can be used to improve situational awareness and therewith improve decision-making. It helps to identify where issues might occur and what could be done for the isolation of parts of a region.

7.2 CASE-STUDY PAPUA NEW GUINEA

On the 28th of February 2018, a magnitude 7.5 earthquake occurred in Hela Province, Papua New Guinea. 160 people were killed and many were injured by the earthquake. The epicentre of the earthquake was 96 kilometres south-west of the capital of the Southern Highlands province (ABC News, 2018).

The reachability model is applied to the case-study of the Papua New Guinea earthquake. First, the model is configured for Papua New Guinea as-is, not including any disaster-related information. However, the model is configured for the provinces that have been struck by the earthquake. The provinces Hela, Southern Highlands and Enga are provinces where a state of emergency had been declared and where a response was needed and Western Highlands is a province where response also came in via Mt. Hagen. These provinces are to be included in the model as-is configuration. For this situation, a visualisation dashboard is created. Then damaged roads and airports are included in the model and the model is updated to reconstruct the disaster context with the model. Then a visualisation dashboard of the reconstructed disaster is created. Both visualisation dashboards are compared. Thereafter, the model outcomes are combined with humanitarian parameters derived from other assessments to analyse how the reachability model could be used in this case-study, using information about victims and affected communities. This section ends with a conclusion where the feasibility of the model in a disaster context is evaluated on both the practical side as the technical side.

7.2.1 Configuring model as-is

The province names of Hela, Southern Highlands, Western Highlands and Enga are inserted into the model and the airports where the reachability is measured from are Tari Airport, Moro Airport, Mendi Airport, Mount Hagen Airport and Komo Manda Airport. The choice for these airports is based on the access constraints map from the World Food Programme that is illustrated in Figure 7.5 and the larger places in the area that have an airport are selected for the model.

The average speed that can be driven in the area is roughly estimated at 50 kilometres per hour because distances are larger and there are fewer junctions and crossings. Whenever there is speed information available in the graph, that speed is included in the calculations. The road qualities are all set to 1, assuming that the network is functioning as it should and the radii for which the reachability is measured are [20, 40, 50, 60, 70, 90, 100, 130, 170, 200, 230, 250] in minutes. The area of this case-study is much larger than the previous case-study, therefore the range of radii is much larger. The whole area should be reachable within 250 minutes.

7.2.2 Visualisation dashboard road network as-is

The previously determined specifications are inserted in the model and the visualisations that the model produces are combined into a visualisation dashboard. The visualisation dashboard is illustrated in Figure 7.4 where the reachability of the region, the road quality of the network and topological information of the network can be interpreted. The black side-bar indicates the date set on the 27^{ht} of February, which is a day before the earthquake happened, the location, the routing type, the time step and the number of roads still intact and broken.The dashboard looks different from Figure 7.1 because of the different shape of the geographical map.

The upper left figure displays the reachability in minutes travel time measured from the five specified airports combined. The area around Komo and Tari, which is the green area on the left of the figure with two blue airport dots close to each other, shows a relatively reachable area. While there are some segments in the north of the country that have significantly longer travel times. The black dots and the thicker black line that goes along multiple edges shows that there is an important thoroughfare that connects the network. It shows that some parts of the network are hard to reach from these airports.

The upper right figure shows the road qualities in the region, indicating them in a colour ranging from red to green. All roads are green because the road qualities are set to 1. The road qualities are set to 1 because the roads in the network are assumed to be in perfect condition by default. The width of the roads indicate the relative criticality of this road for connecting different parts within the network.

The lower left plot displays the node betweenness centrality distribution of the four provinces of Papua New Guinea. The plot has a quite different shape compared to the one from Sint Maarten. As mentioned previously, it’s desirable for a network to have a low number of high dependencies in

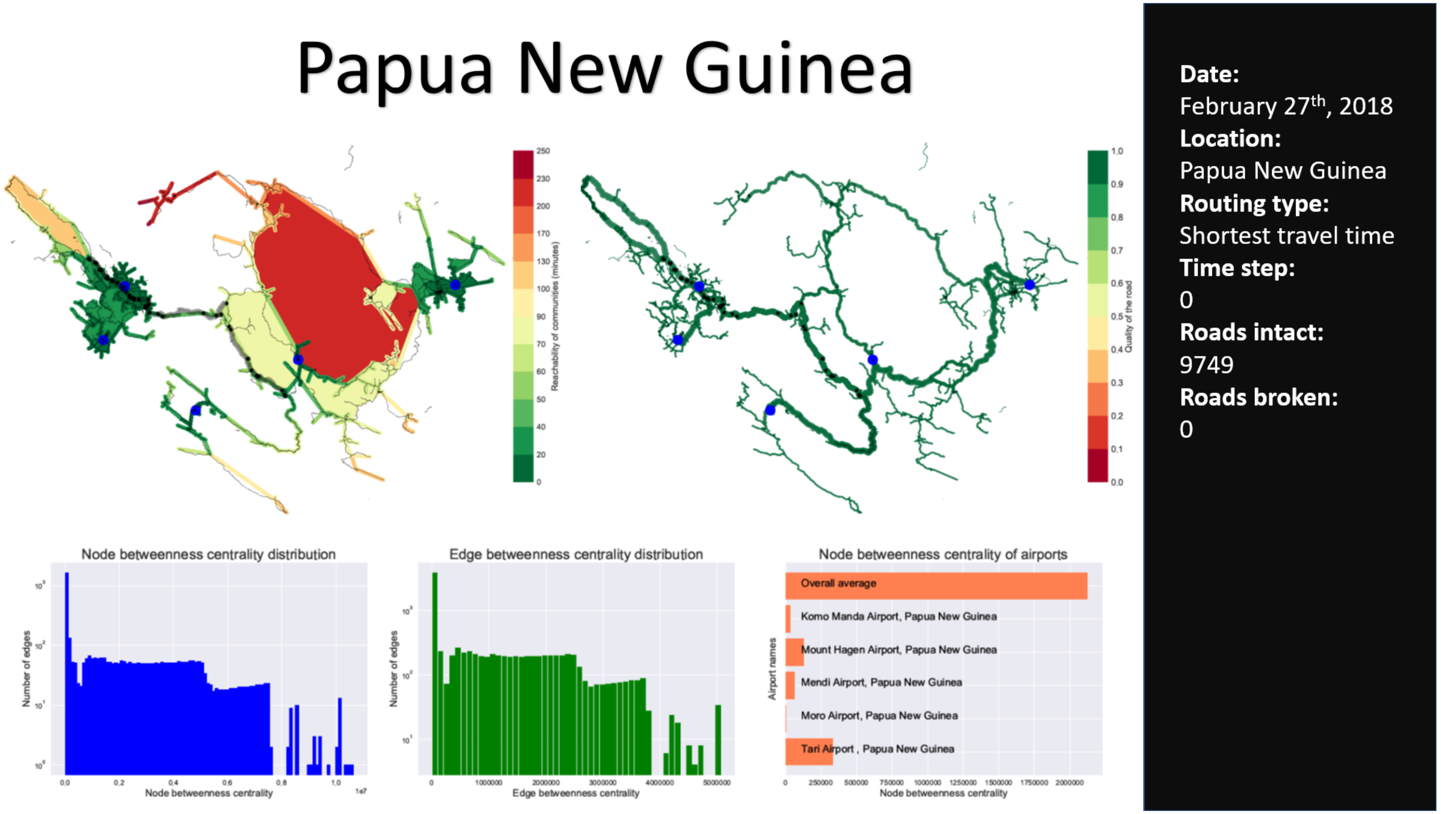

Figure 7.4: Visualisation Dashboard of Papua New Guinea in a pre-disaster context. Lower left: shows how the node betweenness centrality is distributed over the nodes in the network. Lower middle: shows how the edge betweenness centrality is distributed over all the roads in the network. Lower right: compare the betweenness centralities from the airports and the overall average in the network. Upper left: Shows the reachability of Sint Maarten in minutes. Wherein the blue dots are the airports, the black dots are the most important road junctions that connect the region with the entry points, the wider black edges are the most important road segments that connect the region with the entry points. Upper right: shows an overview of the road quality, green means the quality is good, red means the road is not working. Blue and black dots have the same meaning as in the upper left figure. Right sidebar: metadata of the road network and context.

the junctions. However, this graphs displays that there are many nodes with a very high betweenness centrality, making the network relatively fragile. If any of these high betweenness centrality junctions get damaged, and impassable, a lot of shortest routes will become neutralized, being replaced for a longer route. This leads to a lower reachability in the network.

The same can be said of the edge betweenness centrality that is displayed in the lower middle plot. This plot shows the same shape as the node betweenness centrality and that can be explained by the fact that many of the important roads barely have any road exits, which gives them a similar betweenness centrality as the nodes they're connected to.

In the lower right side, the plot shows the betweenness centrality of the airports comparing them among themselves and to the overall average. All airports have a relatively low betweenness centrality compared to the overall average. Making their locations not very suitable for reaching different parts of the network. However, of all the airports taken into consideration, Tari Airport has the best centrality score.

It has to be mentioned that as the betweenness centrality is based on the number of shortest routes, a very high number of nodes in one particular segment of a graph, gives the nodes in this segment automatically a higher betweenness centrality. However, these nodes do not completely reflect the number of people that live in a certain area. Therefore the betweenness centrality should always be looked at with a certain level of judgement.

The dashboard supports the situational awareness of the road network because it gives an overview of the reachability in the network. The dashboard indicates that the four provinces Enga, Hela, Southern Highlands and Western Highlands are not very well-connected and that the network is fragile. There are quite some areas that take very long to reach from any of the big airports. Next, the earthquake impacts are included in the model to observe what the effects of the earthquake is on the reachability in these provinces.

7.2.3 Reconstructing disaster context

It's not possible to completely replicate the disaster situation, because there is not enough information available about exactly which roads have been damaged and to what extent. However, an approximation could be made by consulting the access constraints map from the World Food Program (2018) that is displayed in Figure 7.5. In this figure, it can be interpreted which roads are closed and which airports are operational. Operational airports are assumed to be usable by relief organizations. Of the previously included airports, it seems that Komo-Manda Airport is only accessible by helicopters since the earthquake. Therefore, this one is omitted from the model. The road that is illustrated by a thick red line connected to Moro is closed and therefore given a road quality of 0 in the model. The road represented by the thick green line is open and set to 1. And the road represented by the thick yellow line is restricted and therefore the road quality is set to 0.5, making travelling along this road more time-consuming.

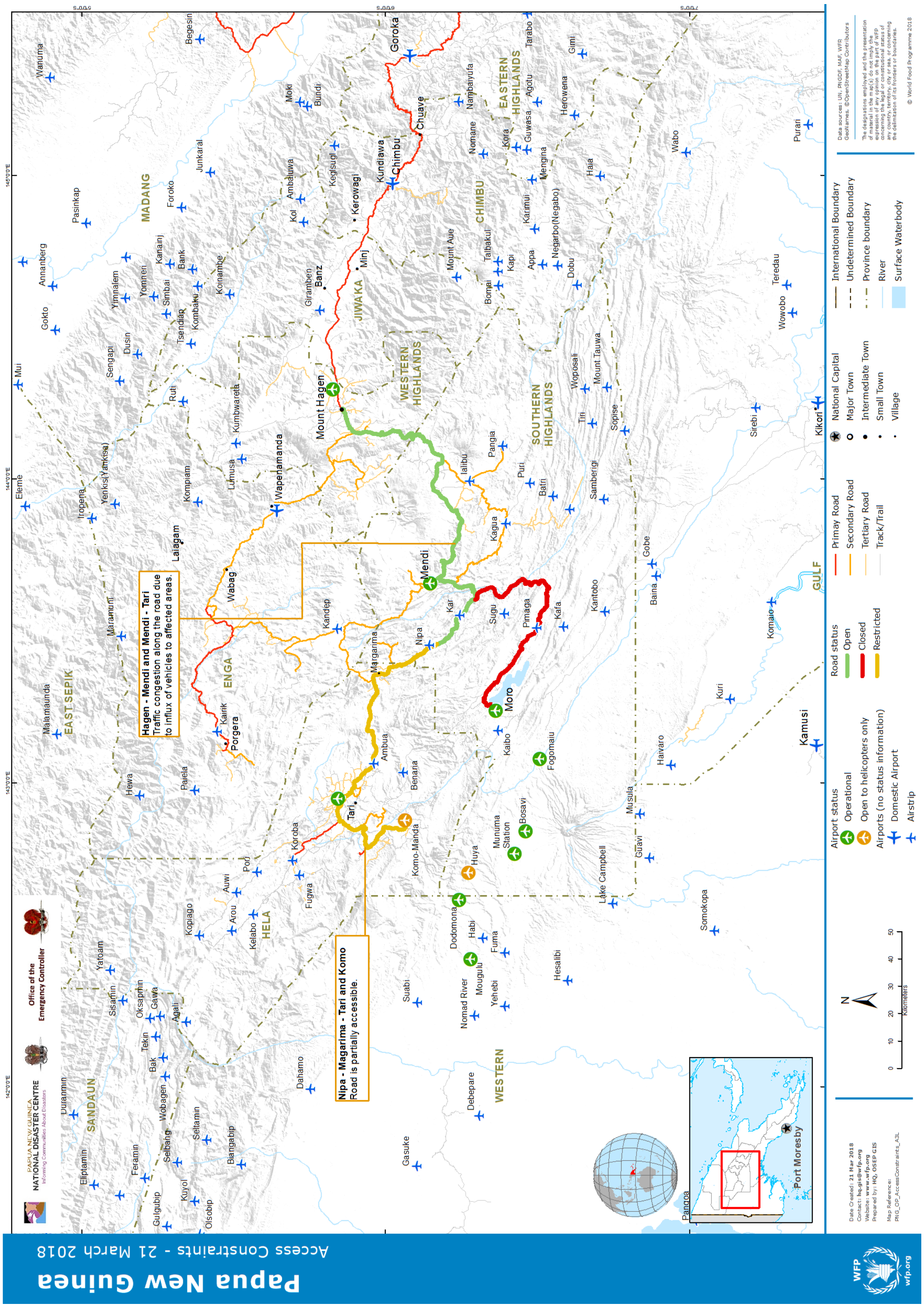

Figure 7.5: Papua New Guinea Airport access (World Food Program, 2018).

7.2.4 Visualisation dashboard of disaster reconstruction

In Figure 7.6 the visualisation dashboard of Papua New Guinea in the reconstructed disaster context is displayed. The difference in model input compared to the pre-disaster dashboard is that Komo-Manda Airport is omitted from the model and that 2267 roads are now broken. This reconstruction is based on the information from the World Food Programme visible in Figure 7.5. In the road quality figure (upper right) it can be seen that one thoroughfare is closed and therefore indicated with a red colour. Another road is indicated with a yellow colour, which is the road that is considered restricted, making travel times longer on this road.

How these changes affect the reachability of the four provinces in Papua New Guinea can be interpreted from the reachability map located in the upper left of the dashboard. The area located around where Komo-Manda Airport has become less reachable. Also, some other parts in the map have shifted a bit more towards red. The changes are visible, travel times have become longer to some parts of the region and it's possible to identify which roads or airports have caused this. The betweenness centrality plots haven't changed much. The change in the network isn't of enough significance to change the plots. Only the omission of Komo-Manda Airport is visible in the lower right plot.

7.2.5 Combining model outcomes with humanitarian parameters

The reachability of the four provinces in Papua New Guinea is visualised and it can be interpreted from the visualisations how long it takes to reach different parts of the area. The findings from the reachability model can be more significant when combining these with humanitarian parameters, such as information about victims and affected communities. During each disaster, many organisations such as the European Union and the United Nations create reference maps that indicate for example where a disaster has struck, where victims have been located or where landslides have occurred. In Appendix I two assessment maps of the Papua New Guinea earthquake are displayed. Just as in the previous case-study, these are assessment maps that are usually not available in the first days/weeks after a disaster has occurred. However, the information from these post-disaster assessments can be used to analyse how the reachability model can be used when combined with information about victims and affected communities. This information is collected from the start, so it's assumed that this information reaches the aid workers in the beginning. Figure I.3 shows a situation overview indicating the number of killed, injured or displaced people from different areas and more information (European Union, 2018) as of March 12^{th}. The knowledge of where injured people are could be useful when combining it with the reachability map. When injured people are difficult to reach, solutions need to be found to fix this problem. Figure I.4 displays the villages that are affected by the earthquake (United Nations Papua New Guinea, 2018). It gives a quick overview of where assistance may be needed and what the consequences of the lack of reachability in a certain area may be. First, the reachability visualisation dashboard is combined with the information from the situation overview in Figure I.3. Then the dashboard is combined with the information from the affected population overview in Figure I.4. Thereafter in the next paragraph, a conclusion is drawn for how

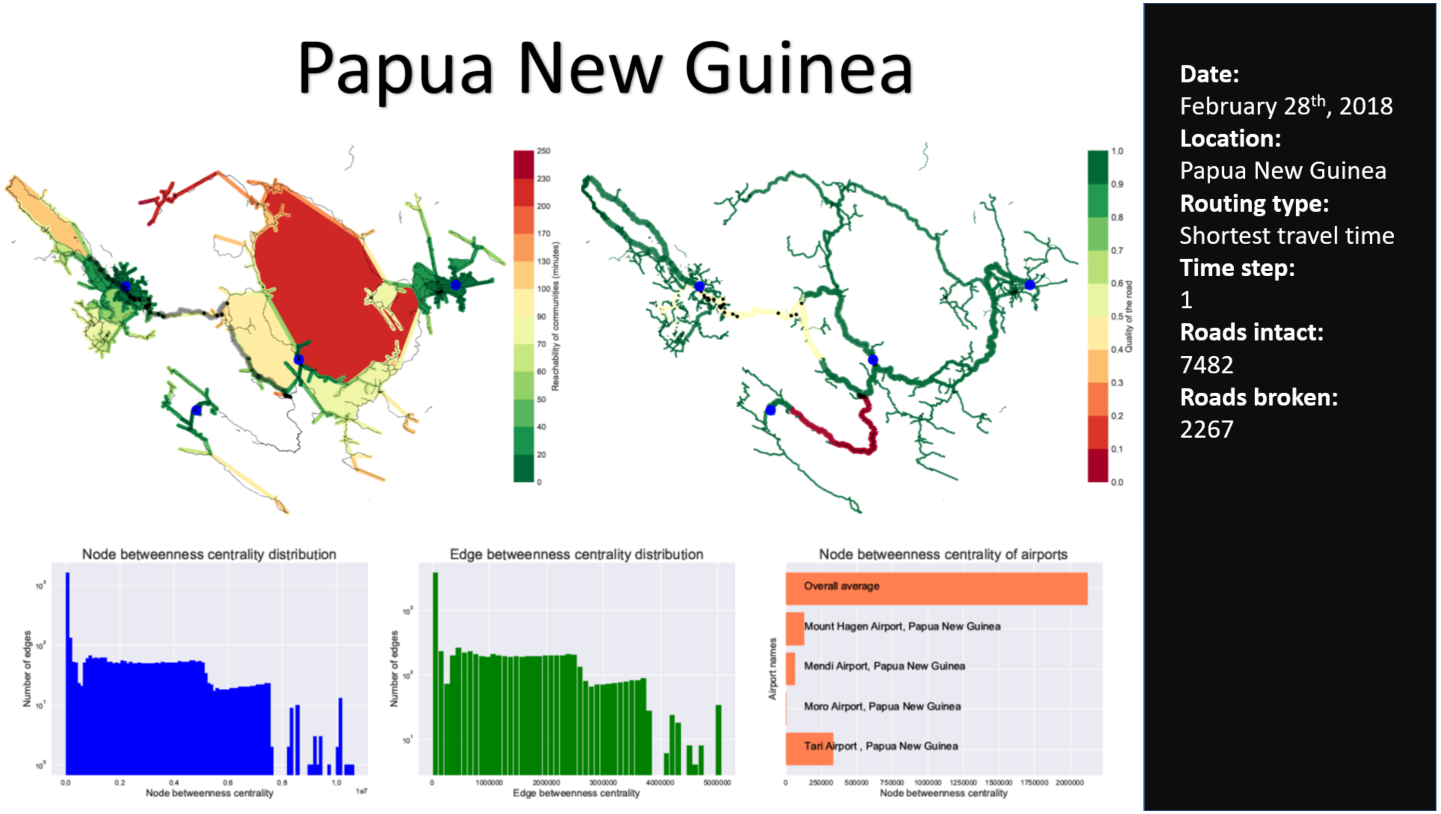

Figure 7.6: Visualisation Dashboard of Papua New Guinea in the reconstructed disaster context. Lower left: shows how the node betweenness centrality is distributed over the nodes in the network. Lower middle: shows how the edge betweenness centrality is distributed over all the roads in the network. Lower right: compare the betweenness centralities from the airports and the overall average in the network. Upper left: Shows the reachability of Sint Maarten in minutes. Wherein the blue dots are the airports, the black dots are the most important road junctions that connect the region with the entry points, the wider black edges are the most important road segments that connect the region with the entry points. Upper right: shows overview of the road quality, green means the quality is good, red means the road is not working, yellow means that the road is restricted to a certain extent. Blue and black dots have the same meaning as in the upper left figure. Right sidebar: metadata of the road network and context.

feasible the model is in terms of technical and practical feasibility, and it's elaborated on what the added value of the model is when combining it with information about victims and affected communities.

The situation overview map of European Union (2018), as displayed in Figure I.3, shows that the highest number of affected people according to this map are nearby Komo (11.700 people) and nearby Pai (12.000 people). When combining this information with the visualisation dashboard of the disaster context, it can be seen that the blue dot that indicates Tari Airport, is able to connect both locations with affected people to relief within approximately 60-100 minutes. When comparing this to the reachability of the area initially as displayed in Figure 7.4, both locations could have been reached within approximately 20-40 minutes. This is quite a difference and should be taken into consideration when conducting relief operations. Furthermore, the location where there are 5.300 affected people near Kutubu Lake, is a location that can not be reached considering the disaster context where one road is completely closed according to Figure 7.5. The visualisation dashboard of Figure 7.6 shows no colour on the road where the 5.300 affected people are located. This means that there is no reachability within the measured scale, which is 0 to 250 minutes. This is a finding that should be taken into serious consideration. A finding like this could indicate that alternative measures should be taken in order to reach these affected people, such as preparing one or more helicopters in order to reach these people that are both affected and isolated.

The population overview map of United Nations Papua New Guinea (2018) in Figure I.4, shows what villages are affected by the earthquake and where they're located. What strikes is the high density of affected villages nearby Mendi and nearby Tari. When exploring the reachability for relief organisations to these affected villages in the disaster context, Figure 7.6 is consulted. The reachability dashboard indicates that the area around Tari is well-connected and reachable within 20 minutes, which is thanks to Tari Airport. It should be noted that when Tari Airport is damaged, this situation will change completely. The area around Mendi does not have a lot of roads like Tari. A consequence of this is the fact that the road going through Mendi is very thick, meaning that it's a critical road for connecting the network. The reachability around Mendi is reasonably good, as long as it's close to the road. The roads around Mendi are reachable within approximately 20-60 minutes. However, if one of the affected villages is located further away from one of the roads, the reachability will become different and more difficult to measure. Off-road reachability is not included in this research.

Combining impact assessment maps of the Papua New Guinea earthquake with the reachability visualisation dashboard of Papua New Guinea creates added value for the situational awareness during the disaster response phase. It helps to identify critical roads and isolated villages that are in need of relief. The time it takes to reach certain areas is useful knowledge for the relief organisations to take into account during the planning of logistics operations.

7.3 CONCLUSION OF MODEL FEASIBILITY

In this chapter, the reachability model is applied to two real disaster situations that have happened in the past year. The goal of this chapter is to evaluate whether the model can be applied to a disaster situation seamlessly and if helps to improve situational awareness. Section 7.1 shows that the reachability model could be applied to Sint Maarten with as a result a visualisation dashboard displaying the reachability of different parts, and what roads or entry points support this reachability. The model set-up is fast, and there is quite some information available for the road network of Sint Maarten, making the application easy. When comparing the pre-disaster reachability model output and the post-disaster reachability model output, the changes are visible. Especially when the model output is combined with humanitarian parameters from damage assessments of the disaster-struck area, additional insights of the disaster situation are yielded. Therefore, based on the case-study where the reachability model is applied to Irma's disaster on Sint Maarten, the model is considered both technically and practically feasible. Technically because the model set-up is very fast, and the adaptation of the road data easy. The model is practically feasible because of the additional insights the reachability model offers leading to an improved situational awareness.

However, Sint Maarten is a relatively small region and an island, and there is a high availability of road network information on OpenStreetMap. Often disasters occur in areas that are much larger with much less information available. Therefore the second case-study is conducted for the earthquake of Papua New Guinea of February, to evaluate the technical and practical feasibility for a more complicated case. More complicated in the sense that the disaster-struck area is larger and that there is fewer road data available. When applying the reachability model to Papua New Guinea, the configuration of the model for this large area takes a lot longer. Still, the runtime of configuring the model is around 15 minutes, instead of 2 for Sint Maarten which are both short times compared to how long it usually takes to create assessment maps. Setting up the model was successful, even though it is on a much larger scale then Sint Maarten. However, for Papua New Guinea, a lot of information is missing of the street names attributed to the edges. This makes it more time-consuming to adjust the road quality for specific road segments. It's still possible by looking up the edge-id information on OpenStreetMap. The reachability visualisation of Papua New Guinea is interpretable and all (known) roads are included. However, it's assumed that there are a lot of villages that need to be reached on foot, and these pedestrian roads could not be included in the model, making the overview of the situation less complete. Moreover, the reachability maps are combined with humanitarian parameters derived from maps showing the affected populations. This gives additional insights that could increase situational awareness and support decision-making. Taking into consideration that only the drivable roads are included, the model still gives a view of the reachability in the area, that adapts to changes in the road network. It can be concluded that also in a much larger area with less information, the reachability model is technically feasible because the model could be implemented within a short time compared to usual assessments, and the input data could be changed easily as well. Furthermore, it can be concluded that the reachability model is also practically feasible because it also performs well in a complicated situation with less information, as it yielded additional insights that could support relief efforts in a sudden-onset disaster.

It can be concluded based on both case-studies that the reachability model can improve situational awareness and therefore support aid workers in the response phase of sudden-onset disasters. Especially in the golden period of the response phase, as for both case-studies, the reachability model is configured rapidly, which gives it a strong advantage to conventional assessments. Two case-studies are conducted in this chapter to evaluate the feasibility of the reachability model in different disaster situations. The most important differences between the two case-studies are the scale of the area and the availability of road data. Sint Maarten is small in scale and has a high data availability, while Papua New Guinea is large in scale and has a relatively low data availability. These differences did not affect the feasibility of the reachability model application much. Only the lack of road data in Papua New Guinea resulted in slightly more time spent on adjusting the road qualities. The conclusion that the model is applicable to both case-studies without being affected too much by the differences in contexts, shows that the reachability model works well in different contexts. Therefore it's concluded that the reachability model is generalisable and can be applied to any other country. To evaluate whether the reachability model could be of added value in practice, experts are consulted in the following section to find out whether the conclusions from this chapter are supported by aid workers in the field.

7.4 EXPERT EVALUATION

To evaluate the feasibility of the model further based on the conducted case-studies, field experts are consulted to verify whether the model offers insights that could potentially be of value for relief operations. A semi-structured interview is set-up and is conducted with two field experts to obtain information. A summary of the interview is given in Appendix J by providing a list of the interview questions in bold font, with the summarized answer of the interviewee below the question. The semi-structured interview consists of six questions. The first three questions focus on the interviewee's experience in disaster relief operations. It's asked whether the interviewee has been involved in relief operations on Sint Maarten after hurricane Irma or in relief operations in Papua New Guinea after February's earthquake. The other two experience-related questions ask about which decisions are critical in the response and what information related issues are involved in these decisions.

After these questions, the interviewees have been introduced with the model outcomes from the case studies and asked whether they see a potential for this model to improve situational awareness. Also, it's asked what kind of decisions could be supported as a consequence to improved situational awareness and what limitations of the model are that could be taken into consideration for the model to reach full potential. These questions are set up like this to first create an unbiased view of the decisions that are made in relief operations, and then see how the model can be used within the process to add value.

The experts that are interviewed are people who have been involved in the response operations on Sint Maarten. One of them as part of the Dutch Royal Navy, and the other as part of a response team from the United Nations. They're considered experts because they have been involved in multiple relief operations in disasters.

The experts have been asked about their view of the feasibility of the model, but also on current limitations of the model that may manifest in future potential. In the following paragraphs, their view on the subject is described.

7.4.1 Feasibility of the model

In the interview, the interviewees have been asked whether they think the model could support decision-making in relief operations in a sudden-onset disaster. Their view is discussed in this paragraph.

According to the first interviewee (UNDAC), one of the most important constraints in the disaster response is the time it takes to receive information about the disaster situation. The model offers a strong advantage in the time it takes to produce a situational overview of the reachability compared to conventional information collection processes. The model could support decisions on determining the priorities certain areas get for receiving aid. Also, the reachability model could be used to determine where shelters and (temporary) medical facilities should be placed, to compensate for a low reachability in certain areas.

The second interviewee (Dutch Royal Navy) agrees that the model could be helpful for determining locations for (temporary) medical facilities. The model seems especially relevant for first-responders that are looking for casualties or that are transporting critical patients. Furthermore, it's interesting to compare the reachability of an area before and after a disaster occurs, because that gives insight in the changes that have occurred in the area, indicating what common transport routes might need to adapt to a new situation.

7.4.2 Limitations of the model

Both interviewees also have an opinion of some of the model's limitations and some refinements that may increase the potential of the model feasibility. The model does not include how reachability is influenced by traffic congestion. This is an important factor for Sint Maarten because many tourists visit the island all year round. Also, if the model includes humanitarian parameters so that the model also visualises affected people on a map, it would have more added value. Furthermore, the model could have more potential when it includes the possibility to simulate multiple scenarios. The second interviewee (Dutch Royal Navy) agrees with the point that the traffic congestion is an important factor that is currently not included in the model. However, these are features that are not included in the scope of this research due to time constraints. These features are topics that could be considered for future research.

7.4.3 Conclusion of expert evaluation

Both interviewees seemed excited about the model and believed in its potential to add value during disaster response operations in terms of situational awareness. In the case-studies, it is mentioned that the model could be implemented in different types of disaster areas and that it can analyse the network quickly. Combining the reachability model with humanitarian parameters from other impact assessments gives insights that are of added value to response operations. From the expert interviews, it became clear that a strong point of the model is the rapidity of the model to produce results. The model is unique in the assessment of the disaster-struck area in the very beginning of the response phase. The model is found useful for prioritizing relief activities and placing medical facilities or shelters. However, the model could be more successful if it could include humanitarian parameters in the visualisation as well.

Overall, the model could add value to relief operations as it collects information and combines it in an interpretable visualisation. Even though, there are limitations and many features that could be added to increase the potential of the model, the model in its current state is concluded to be an added value for relief operations. In the next chapter, the outcomes of the model and this research as a whole is reflected upon and the recently mentioned limitations of the model will also be elaborated on.

8 DISCUSSION

"One of the basic rules of the universe is that nothing is perfect. Perfection simply doesn't exist.....Without imperfection, neither you nor I would exist"

Stephen Hawking

The results of the reachability model evaluation of the previous chapter are discussed and reflected upon in this chapter. In this research, a reachability model is designed to improve the situational awareness in the very beginning of the response phase of sudden-onset disasters. However, this research and the model have limitations, because it is built upon some assumptions. Furthermore, it's to be discussed to what extent the model can be considered valid, considering the fact that this research did not include proper validation. Moreover, the practical implementation is discussed in this chapter, to reflect upon the potential of the model the be useful in reality.

The limitations of this research are discussed in this chapter while focusing on three aspects. The limitations of the model are discussed, then the limitations of this research, in general, are discussed and lastly the assumptions on which the model relies are described, and to what extent these assumptions impact the performance of the reachability model. After the three types of limitations, the potential practical implementation of the reachability is critically discussed.

8.1 LIMITATIONS OF THE REACHABILITY MODEL

The reachability model is feasible to improve situational awareness in the response phase of sudden-onset disasters. It has the potential to become useful for aid workers to increase their effectiveness in their relief operations, especially in the beginning of the response phase. However, there are some limitations of the model that are identified and described in this paragraph. In Appendix J, an interview is conducted with experts and from these interviews, some of the model's limitations have been identified.

One of the limitations that were mentioned is the lack of the inclusion of traffic congestion in the model. When a disaster occurs, it can be expected that people try to evacuate, while at the same time aid workers want to get into the area as quick as possible. The traffic congestion especially played an important role in the aftermath of hurricane Irma on Sint Maarten. A reachability model that doesn't take this into account on an island with a sparse infrastructure will be of moderate added value. Including the traffic congestion in the model is something that is not within the scope of this research, but is something that could be focused on in future research.

Another limitation of the reachability model is that humanitarian parameters are not included in the model. Including these parameters are outside of the scope of this research, but it could add value when it's implemented. Currently, the research gives information about the reachability of an area and if this information can be combined with knowledge about the locations of affected people in a disaster area. This could be helpful for improving situational awareness in the response phase. However, future research could focus on including humanitarian parameters to centralize more information in the model to improve situational awareness.

The last identified model limitation is that the reachability model only indicates the reachability for areas that are directly adjacent to a road. In the case-study of Papua New Guinea, there were many villages that were not close to any road, which makes it impossible to calculate the reachability of these particular villages. It's up to future research to also include calculating the reachability of villages that are not adjacent to any road.

8.2 LIMITATIONS OF THIS RESEARCH

A limitation of this research is that it has not been researched whether the reachability model actually improves situational awareness and that this leads to a better performance of relief operations. Also, the reachability model hasn't been validated in this research, because the validation of the model outcomes is very time-consuming. As the validation has not been done, it's not possible to know if the model is correct and if the insights it gives are accurate. These are difficult issues that can not be addressed easily. However, this deserves attention in future research.

Validation of the model addresses the question whether the designed reachability model represents an accurate representation of the real-world system (Dam, Nikolic, & Lukszo, 2013).Dam et al. (2013) describe two views of validation. The traditional view, that concerns whether the model represents the real-world situation accurately, and the view applied to models for which there is no real-world system available to compare with, that focuses on whether the model is useful and convincing. In this case, there is a real-world system available where the reachability model can be compared with, therefore the traditional view on validation would suffice. For the reachability model, validation should question whether the reachability model uses roads, travel times, distances et cetera, are corresponding to the real-world parameters that are represented. To validate the designed reachability model, the approach could be to prepare semi-structured interviews with several experts and conduct literature research to validate whether the model is able to represent the situation accurately. The case-studies conducted in Sint Maarten Papua New Guinea could then be validated to determine the accuracy of the reachability model. Questions asked to experts should focus on their experience with what the effect was of worsened road conditions and if the reachability model gives an accurate view of the actual situation. In literature research, the focus should be on finding information about what transport movements on the island were made and how long these took, and if these were influenced by road conditions. Also, the completeness of the road network should be validated, this could be done by both literature research and expert validation. The validation of this reachability model is a topic that can be focused on in future research.

The reachability model, and its outcomes, when applied to the case-studies of Sint Maarten and Papua New Guinea, is evaluated by conducting semi-structured interviews with two experts. Ideally, more experts should have been interviewed. Two experts are not many, which can be seen as a limitation of the evaluation of the model. The reason why only two experts are interviewed is because of the time constraints of this research. It is recommended for future research to approach more experts on this matter to do a more thorough evaluation. However, the experts that have been approached for interviews are people who have a lot of experience in the field and are considered as a valuable source of information.

8.3 CRITICAL ASSUMPTIONS

The reachability is built upon several assumptions, and the research itself also assumes some causal relations that might not be correct. The reachability model uses OpenStreetMap data to create a graph network that forms the foundation of the model. One of the major assumptions the model relies on is the assumption that the data provided by OpenStreetMap is correct. If the data isn't correct, the model is worthless.

The road quality has an important role in the reachability model because it indicates whether a road is broken or not and this influences the travel time it takes to travel across a road segment. The road quality is on a scale from 0 to 1. However, it is not defined when a road is considered to be 0, or when a road is 0.4. In the case-studies, the road quality is more or less an approximation for the sake of simplicity. The choice of the road quality value does have a strong effect on the reachability within the model, therefore should be taken into account as an assumption.

To calculate the travel time on edges in the reachability model based on the road quality, Formula E.4 is used. The travel time across an edge is determined by the length of the edge, the speed that's travelled on the edge (based on the maximum allowed speed or average speed), and the road quality. The impact of the road quality on the travel time within the formula is S-shaped. The function of the road quality impact on the travel time is not validated in any way and is assumed to represent a real relation.

The above assumptions need to be considered thoroughly before implementing this model in practice. The outcomes of the model rely strongly on these assumptions, therefore the assumptions should be investigated. The OpenStreetMap data that is used should be validated before the model can safely use this data. Moreover, when using this model in practice, there should be consensus on what road conditions correspond to a value between 0 and 1. The impact of road quality on the travel time should also be investigated and evaluated. When these assumptions are taken care of, practical implementation of the model can be considered.

8.4 PRACTICAL IMPLEMENTATION

For the reachability model to be implemented in disaster situations to support aid workers in gaining situational awareness, some enhancements could be done to improve the user-friendliness of the reachability model. Within this research, the reachability model is a proof of concept. Even though it's relatively quick and easy to use, the user needs to have knowledge of Python or another programming language and the visualisations have to be arranged manually into a dashboard. Enhancements that would make practical implementation easier are to create an interface that looks similar to the visualisation dashboard displayed in Figure 6.9, where roads can be selected and a road quality value can be inserted for a road segment, and that then a refresh button can be pressed, creating an updated reachability model.

The current reachability model in this research allows for making adjustments to the roads by using an Excel file where particular roads can be selected to adjust the road quality values. However, to implement the changes in the model, the Python notebook where the model is made with needs to be opened and the code should be run again. Therefore the model in the current state is easy to use, but it could become user-friendlier. When it's investigated how the road quality should be valued, and there is a proper standard that can be understood by aid workers, there is a potential for this model to be used in sudden-onset disasters by an information manager of the response team. The information manager should then insert new information of the infrastructure continuously in the reachability model and can display the visualisation dashboards for the other aid workers to see and base their decisions on. However, to verify whether this adds value to the effectiveness of the response teams, future research needs to investigate the effectiveness of the model.

When the reachability model as designed in this research is used in practice during the response phase of a disaster, several steps need to be followed to improve situational awareness. In Appendix K, an instruction manual is presented, that walks through the different steps necessary for creating a reachability dashboard. Using this instruction manual, any humanitarian can use the reachability model in disaster situations.

9 CONCLUSION

> "Reasoning draws a conclusion, but does not make the conclusion certain, unless the mind discovers it by the path of experience."
>
> *Roger Bacon*

In the previous chapters, substantial effort is put into the process of designing and evaluating a model that analyses multiple network properties to determine the reachability of disaster-struck areas. This chapter connects the aim of this research as introduced at the beginning with the final outcomes by bringing all the pieces together. First, a short recap is given of the problem situation that is the reason for this research and how it's addressed in this research. Then the research sub-research questions as introduced in Chapter 3 are answered, and by answering all sub-research questions, an answer for the main research question can be formulated, while connecting this answer with the issues raised in Chapter 1. Thereafter, the last steps of the design approach of Hevner et al. (2004) are completed by composing the scientific relevance and the societal relevance of this research from all the insights obtained in this research. Ultimately, recommendations are formulated for future research that needs to be done to work out some of this research's limitations as described in Chapter 8.

9.1 SHORT RECAP

Climate change causes all kinds of hazards worldwide, such as rising sea levels, stronger hurricanes and heavy rainfall. Sudden-onset disasters are a frequent threat to humanity. When a disaster occurs, relief organisations and governments send aid workers to come to the aid of the victims in a disaster-struck country to engage in relief operations. In order for aid workers to conduct effective relief operations in the last-mile of humanitarian logistics, they need to be coordinated adequately which requires a sufficient provision of information about the disaster situation. This information is needed for aid workers to acquire situational awareness in a situation. Situational awareness during disaster response is important for guiding the aid workers in their operations and to reach victims in need of relief in time, and with the right priority. However, often when a disaster has occurred, sufficient situational awareness is lacking, especially concerning temporal and geographic details in the provided information.

A reachability model is designed in this research to improve situational awareness for aid workers in the response phase of sudden-onset disasters. The model is conceptualised, constructed, implemented and evaluated with two case-studies. To determine whether the situational awareness in the response phase of sudden-onset disasters could be improved by this model, the research question that has been formulated in Chapter 3 will be answered.

9.2 ANSWERING RESEARCH QUESTION

In the research formulation in Chapter 3 the main research question has been formulated to address the identified knowledge and is as follows:

> **How can situational awareness in the golden period of the response phase of sudden-onset disasters be improved with a dynamic visual representation of the community reachability by aid workers?**

To answer this question, the four formulated sub-research questions are answered first.

9.2.1 What are the requirements for modelling the network of communities and their reachability?

The first sub-research question is addressed in Chapter 4, by gathering information in a desk research about the requirements for modelling a network of communities and their reachability. It's researched what stakeholders are involved in the issue and it's found that the environment where the issue is located in, consists of a wide range of actors as displayed in Figure A.1 that all share the desire to have a more effective disaster response. The public sector and relief organisations are stakeholders for whom an improved situational awareness seems most relevant. Improving situational awareness agrees with a target of the United Nation's Sendai framework. Furthermore, to model the network of communities and their reachability, the road network needs to be included, with distances, capacity, quality and maximum speeds. Also, the entry points into a country, such as airports and harbours need to be included in a model. Graph theory can be used to measure reachability by incorporating centrality measures, intrinsic network properties and path search algorithms in the model. This reachability can be then visualised in a geographic map and several plots and then combined into a useful dashboard.

9.2.2 How can the reachability of communities be determined and identified?

In Chapter 5, the second sub-research question about how the reachability of communities can be determined and identified is answered. In Chapter 5, the construction of the reachability model is illustrated in a process diagram that is displayed in Figure C.1. All processes of configuring the model are described in this Chapter and demonstrate how open-source infrastructure data from OpenStreetMap is used to create a multi-directional graph where the reachability of all locations in the road network can be determined by using Dijkstra's shortest path algorithm including a weight of travel time, travel distance, or a combination of travel time and road capacity, based on the preferred routing option. This offers an outcome of the reachability of any location from all of the specified airports or harbours. Moreover, the model can be updated frequently to measure the actual reachability. Implementation of the model in Python and verification of the model shows that the model does what it's supposed to do when implemented, therewith answering the second sub-research question.

9.2.3 How can the reachability of communities be visualised?

In Chapter 6, the third sub-research question is answered by visualising the calculated reachability. In Chapter 6, the visualisation of model outcomes is demonstrated by using a green to red colour scale to indicate the reachability of parts within the network. The model is used to determine reachability, and a list of radii need to be specified for the model to determine in what colour bandwidth a location belongs. When this is iterated over all the points in the network, a visualisation is produced that shows the reachability. This is demonstrated for the three different routing options.

To produce more information about the network, road quality visualisations are also produced. Colouring the roads in good condition green, and in bad condition red, on a sequential colour scale. Moreover, plots are also created of topological network characteristics, to analyse the network further. The five produced visualisations are combined into a dashboard, that makes communication of this visual information easier. Overall, Chapter 6 demonstrates how the reachability of communities can be visualised, and thereby answers the third sub-research question.

9.2.4 How can the reachability model support decision-makers to improve situational awareness in disaster management?

To find the answer to the fourth sub-research question, the feasibility of the reachability model is evaluated in Chapter 7. The reachability model is first applied to the disaster context of hurricane Irma at Sint Maarten and is then applied to the disaster context of the earthquake in Hela Province, Papua New Guinea. The reachability model's outcomes in Figure 7.1 and Figure 7.3 illustrate how the reachability of the areas has changed as a consequence of the sudden-onset disaster, compared to the initial reachability of the area. It indicates what roads are causing a decrease in reachability and what roads are critical for the functioning of the network. When these outcomes are combined with humanitarian parameters derived from other impact assessments as displayed in Appendix I, the reachability model could support decisions such as when a helicopter is necessary to be deployed, or what the priority of rebuilding a harbour or airport should be, or where medical facilities should be located with enough supplies, which functions as a sign that it improves situational awareness. The reachability has the most potential when combining the outcomes with information about the affected population.

These findings and the reachability model, in general, have been evaluated by conducting semi-structured interviews with field experts that have been involved in disaster response situations. According to the field experts, the reachability model improves situational awareness and therewith support decision-making by speeding up the process, because the reachability model configures rapidly, compared to other impact assessments. Furthermore, the reachability model can also support the process of prioritizing relief activities and the placement of shelters and medical facilities. The model could be more promising when it also includes affected people in the model, by visualising the affected people on a map together with the reachability.

9.2.5 Main research question

The main research question in this research consists of several elements, and before the research question is answered, all elements are addressed and linked with parts of this research. The main research question consists of two main parts;

1. Situational awareness in the response phase of sudden-onset disasters
2. A dynamic visual representation of the community reachability by aid workers

And the question is how element 2 can help to improve element 1. First, element 1 has to be understood. Element 1 consists of three main elements:

1. Sudden-onset disasters
2. Situational awareness
3. Response phase

Sudden-onset disasters are disasters for which there is little or no warning. The response phase is the phase directly after a disaster strikes where actions are focused on providing medical support to casualties and limiting the impacts a disaster has on a community. Situational awareness in the response phase of sudden-onset disasters is the perception of all elements in the disaster context within a volume of time and space, with a clear understanding of the elements and their development in the near future. Situational awareness in the response phase of sudden-onset disasters is supported by data of the disaster environment.

To address the main research question in this research, a reachability model is designed to produce a dynamic visual representation of the community reachability by aid workers, which represents element 2 of the research question. The reachability model is dynamic because it allows new data to be inserted adjusting to this new information. The model outputs are a visual representation of the community reachability by aid workers because with colours it's indicated how long or how far it takes to reach any location in a network, measured from an entry point that is determined as the point from which aid workers will come.

To analyse whether a dynamic visual representation of the community reachability by aid workers can improve the situational awareness in the response phase of sudden-onset disasters, case-studies with the reachability model and semi-structured interviews with experts are conducted. The conclusions of the case-studies and semi-structured interviews are that the model could help with a common issue in situational awareness in the response phase of a sudden-onset disaster. That is the issue that a lot of information aid workers currently receive takes a lot of time to reach them and is often not complete in geographic details. The designed reachability model can be configured rapidly in the golden period of disaster response and offers geographic details of information and therefore supports situational awareness.

Furthermore, according to experts that have been interviewed in this research, the reachability model can support the prioritisation of relief activities in the response phase and support determining the placement of medical facilities and shelters for victims of a disaster. With the reachability model's limitations taken into account, this particular dynamic visual representation of the community reachability by aid workers can help to improve the situational awareness of aid workers in the golden period of the response phase of sudden-onset disasters.

The conclusions of the case-studies and the expert interviews answer the main research question to the extent that the designed reachability model could help to improve situational awareness in the response phase of sudden-onset disasters. However, the reachability model does not guarantee improved situational awareness in practice, as it hasn't been tested in an actual sudden-onset disaster yet. Therefore, the main research question is only answered to the extent of the potential that the dynamic visual representation of the community reachability by aid workers carries.

In Chapter 1 the issue is raised that offering relief aid to victims of a sudden-onset disaster is often difficult because there is a lack of situational awareness, which could lead to more casualties than necessary. By answering the research question, the issue is addressed and this research offers an improvement in the effectiveness of relief operations.

9.3 SCIENTIFIC CONTRIBUTIONS

The process of this research is based on the framework of Hevner et al. (2004) and in this paragraph, the additions to the knowledge base are recapitulated. The scientific contributions are added to the framework of Hevner et al. (2004) as illustrated in Figure 9.1. In Chapter 2, a literature review is conducted to discover more about the last-mile of aid delivery and situational awareness in this context. Chapter 2 concludes with an identified knowledge gap in the literature. There is a lack of knowledge about how the mapping of community reachability by aid workers could support situational awareness and coordination of relief organisations in the golden period of disaster response. The main scientific contribution of this research that aims to fill the knowledge gap is the following:

- **Designing a fast data-driven generalisable information system for disaster management**
  The model that's designed in Chapter 5 uses open source-data from OpenStreetMap and is an information system that can be set-up very quickly. Furthermore, any location in the world can be specified and the model will adapt to the query. Therefore it's data-driven and is user-friendly. There aren't any dynamic data-driven models used in disaster-response yet that can produce an overview of the situation within an hour, this is, therefore, a scientific contribution of this research. Most importantly, the methodology that is described in order to create the reachability model is one that helps aid workers in the first moments of disaster response. All geographic visualisations in the disaster response so far take long before they are created, while the presented reachability model can be readily available directly as the response phase commences.

Besides the main scientific contribution, there are two other scientific contributions that come forth from this research, which are the following:

- **Combining reachability model outcomes with humanitarian parameters to support decision-making**
  In Chapter 7, the reachability model is applied to two case-studies and the outcomes are combined with humanitarian parameters in a disaster. A scientific contribution of this research is the knowledge that combining this type of reachability model with humanitarian parameters in sudden-onset disasters yields insights that can support decision-making. Reachability models are used in other contexts. However, applying reachability models in the humanitarian context is a contribution to science, as it hasn't been reported yet.

- **Combining both topological metrics and intrinsic properties of a road network using graph theory**
  When a multi-directional graph is created from a specified road network, topological metrics can be calculated using graph theory. However, in this research, topological metrics, such as the distance between nodes, and path search algorithms are used together with intrinsic properties of the network, such as road capacity, maximum allowed speed, and road quality. These metrics are combined to measure the Dijkstra shortest path and therewith the reachability in the network. Measuring reachability by combining these metrics is a scientific contribution.

9.4 SOCIETAL RELEVANCE

This research focuses on improving situational awareness in the response phase of sudden-onset disasters. The effectiveness of disaster response operations can make a difference in the number of casualties from a disaster. This research aims to improve situational awareness by getting more information, faster. This means that when relief organisations decide to use the designed reachability model, they can make informed decisions quicker than before, which may allow them to provide emergency relief to victims that otherwise wouldn't be helped in time. Both governments and relief organisations could profit from using this reachability model as it allows the user to quickly create an overview of the situation and lets the user make appropriate decisions when needed. Overall, the societal relevance of this research can be found in the way it could help to bring relief to victims earlier, that might save lives in some cases. The societal relevance of this research is added to the framework of Hevner et al. (2004) as illustrated in Figure 9.1.

9.5 FUTURE RESEARCH

This research is not fully comprehensive and should therefore not be treated as such. This research offers a starting point for future research in this direction. There are several directions that future research could focus on in the extension of this research. In this paragraph, three possible directions for future research are suggested.

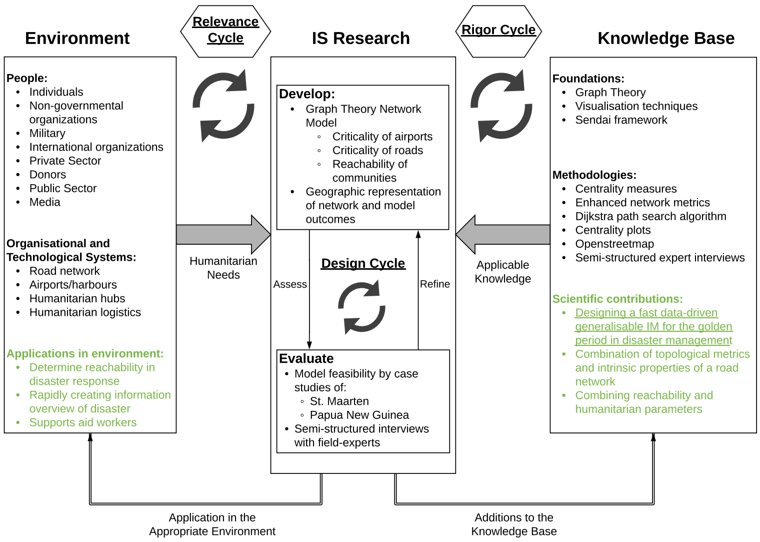

Figure 9.1: Framework of Hevner, March, Park, and Ram (2004) with societal and scientific contributions added

During the semi-structured interviews conducted with disaster response experts, it became clear that the designed reachability model could improve when traffic congestion is included in the reachability. Therefore future research is recommended about how traffic congestion could be included in the reachability model. The research could focus on using real-time traffic data that's also used in Google Maps and include that data in the calculation of travel time from one place to another and evaluate whether this produces added value for the reachability model.

Another future research direction that is suggested is to expand the reachability model by including the possibility of adding spatial data to the model of people that are affected by a disaster and including this in the visualisation outputs. That way, the reachability model also indicates where help is needed on the dashboard, that makes the model even more relevant. Information about affected people or other humanitarian information can be indicated using often used humanitarian symbols. This future research direction could include extending the model to recognise when to use certain humanitarian symbols and placing them on the map where it's relevant. This could improve the communicative quality of the reachability model.

The last suggested future research direction is to explore to what extent the designed reachability model has a positive effect on the effectiveness of the disaster response activities. A research could focus on conducting experiments with the model in disaster situations while measuring key performance indicators to verify whether the model actually works. Furthermore, it could then also be researched if the type of disaster affects the effectiveness of the reachability model.

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A INVOLVED STAKEHOLDERS

In this appendix, the stakeholders that are involved in the response phase of sudden-onset disasters are described according to the decision-makers taxonomy of Verity Think (2013) as illustrated in Figure A.1.

Individuals

Individuals can be categorized into the national population and the international population. The national population can be split into affected individuals, donors and volunteer groups. The international population can be split into donors, volunteer groups and bordering populations. In this research, affected individuals of the national population are taken into consideration for the purpose of the model, the other individuals are not included in the model. The main objective of the affected individuals is to survive a natural disaster and to recover as fast as possible by receiving aid from donors via NGO's. For them, it's especially important that response operations are effective and that they will be prioritised when necessary.

Non-governmental organizations

Non-governmental organizations can be either advocacy organizations or operational organizations. Examples of involved operational organizations are the International Federation of the Red Cross (IFRC), Doctors without Borders (DSF), OXFAM, World Food Programme (WFP) et cetera. These NGO's often collaborate with local NGO's, government and military for the last mile operations to reach affected individuals with relief efforts (Duran et al., 2013). The main objective for NGO's is to 'meet the end beneficiary's requirements' (Thomas & Mizushima, 2005), which could be done by successfully reaching victims with emergency aid supplies while being as effective as possible.

Military

Military responses to natural disasters are more frequent than before, both national and international military involvement (Hofmann & Hudson, 2009). The abrupt and destroying nature of natural disasters calls for a highly coordinated response to the crisis, which is something the military can deliver (Fischer, 2011). The military as a decision-maker can be separated into the National Forces, Multinational Forces, Irregular Forces and Private Military Companies. In this research, only the National Forces and International Forces are relevant. The National Forces are the national army of the government of a country lead by the minister of Defence. Multinational Forces that are frequently involved in humanitarian aid is the NATO (Hofmann & Hudson, 2009). Objectives of military decision-makers are to secure a natural disaster area and to deliver aid to affected individuals or potentially evacuate affected individuals.

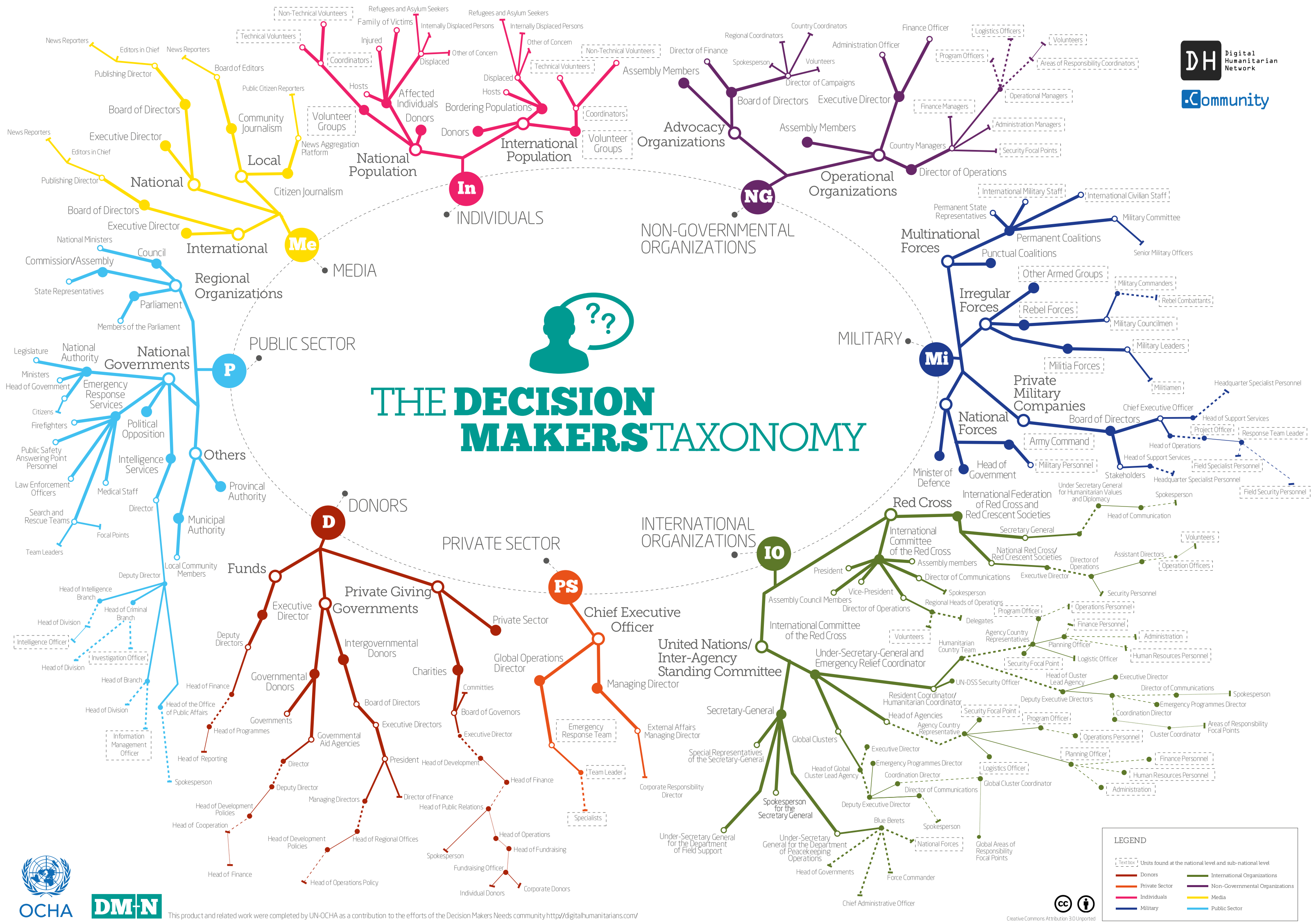


Figure A.1: Decision Makers Taxonomy (Verity Think, 2013)

International organizations

International organizations consist of the International Federation of Red Cross (IFRC) and Red Crescent Societies, and the United Nations. The Red Cross has connections with the National Red Cross within a country, and the United Nations has a specialised department for humanitarian affairs, the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA), that coordinates both international and national humanitarian groups that offer assistance during natural disasters. An important objective of the IFRC is to take measures to prepare for and reduce the effects of a disaster on vulnerable populations by being able to carry out effective relief operations (International Federation of Red Cross and Red Crescent Societies, n.d.). Among many other objectives, UNOCHA aims to create favourable conditions for a successful emergency response during natural disasters (UNOCHA, n.d.).

Private sector

The private sector in an area struck by a disaster has the main objective to restore the business as soon as possible. This is important for the society as a whole, as the economy needs to recover from a disaster, and that can be done by restoring the local trade and business.

Donors

Donors are an important source of money, supporting humanitarian efforts. Donors could be either individuals, governments and funds. An important objective for donors is that their money is used adequately and effectively. Most donations are given after a disaster has struck, making it difficult for relief organisations to have resources to be properly prepared (Kovács & Tatham, 2009).

Public sector

The public sector of a country consist of the national government, and the decentralized provincial and municipal authorities. Areas, where the worst disasters occur, are often relatively poor countries, and on top of that, governments of affected countries are often inexperienced with disaster management and overwhelmed by the impact of a disaster. It's assumed in this research that the public sector relies much on the relief organisations that could be from both international NGO's or national organisations.

Media

According to Olsen, Carstensen, and Høyen (2003), occasionally the media play a determining role in the volume of emergency assistance that's attracted to a humanitarian crisis. This is known as the 'CNN-effect'. The media has the objective to report on humanitarian crises and create awareness globally on a situation. The media attention will affect the donations that are made, which support the relief organisations (Kovács & Tatham, 2009).

B BASIC PRINCIPLES OF GRAPH THEORY

In 1736, Euler started Graph Theory as a branch of mathematics (Kaveh, 2013). Graph Theory is used to describe physical systems whose performance depends on their components and the relative location of these components. The topology of a structure influences the overall performance of this structure, and this topology needs to be well-understood. Graph theory is a powerful tool to model the topology of a structure (Kaveh, 2013).

A graph consists of a set of elements that are called nodes. Each of these nodes is connected to any amount of other nodes (including to themselves) via edges. When a node is connected to itself, this connection is called a loop. A graph is a simple graph when it does not contain any loops. Two nodes are adjacent when there are connected with an edge. An edge is incidental with a node if it's connected with this nodes. Two edges are incident if they both have a connection with the same node. The degree of a node in a graph is the number of edges connected to the node (Kaveh, 2013).

A path is a sequence of nodes where each consequent node is connected by an edge. A simple path is a route from a certain node to another where no node appears more than once. (Easley & Kleinberg, 2010). In the context of this research, a path can be viewed as a route from an airport to a certain village, passing along different parts of the region. The distance between two nodes is the number of steps that need to be taken from one node to reach another.

This research aims to describe the physical network consisting of roads connecting communities in a region or country with nearby airports and to determine how well-connected certain communities are with nearby airports. Graph Theory is a useful method of describing this network because it makes it possible to simplify the actual road network into a model in which calculations can be made to determine how well-connected communities are based on the travel time from the airport to a community, the number of paths going from the airport to a community and the robustness of certain connections.

C | DETAILED MODELLING PROCESS

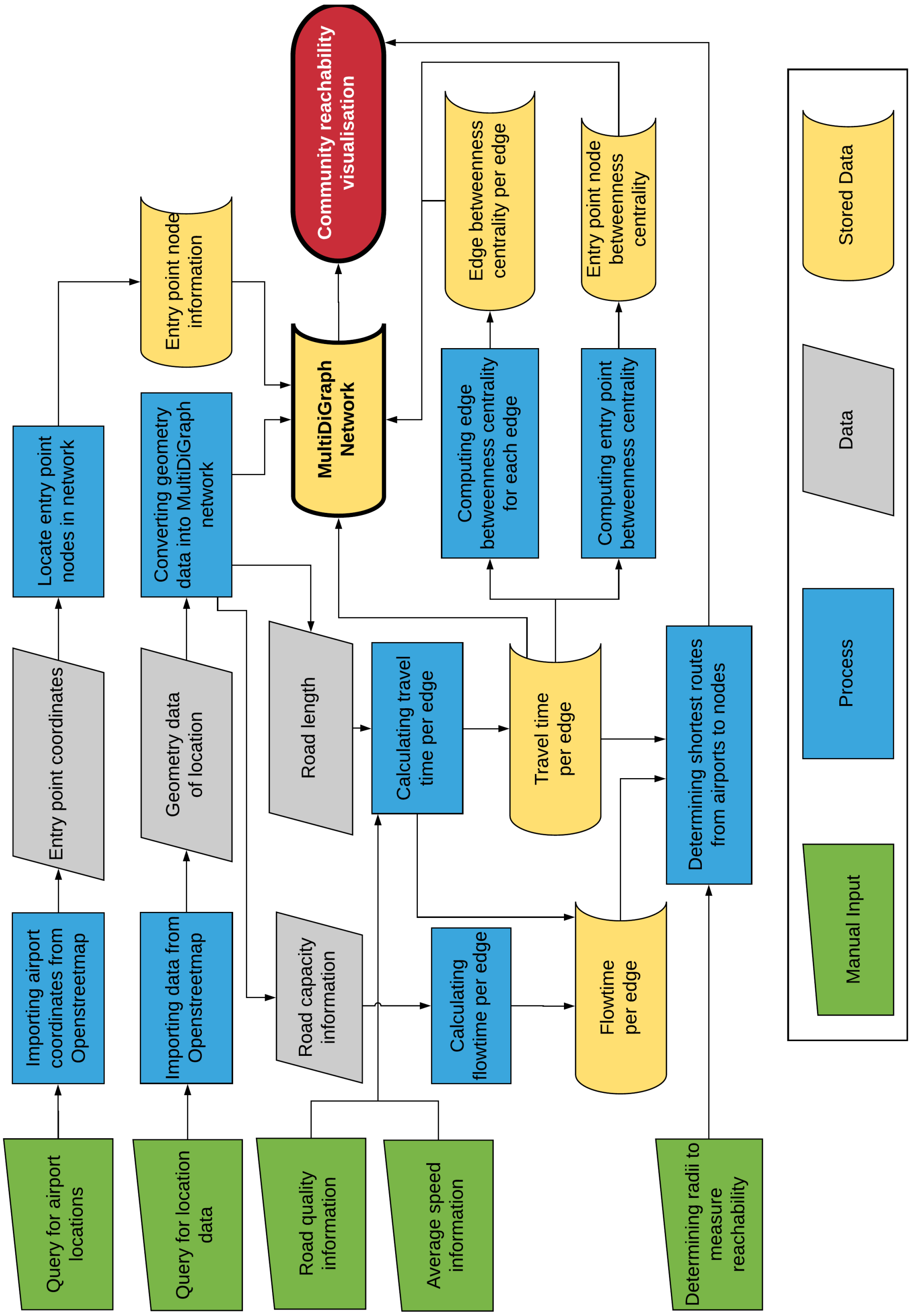


Figure C.1: Process diagram of the reachability model

D USED PYTHON PACKAGES

Table D.1: Installed Python packages and the version numbers

Name	Version
geopandas	0.3.0
git	2.1.11
json	2.0.9
matplotlib	2.2.2
networkx	2.1
numpy	1.14.4
osmnx	0.8
pandas	0.22.0
sys	3.6.0 | Anaconda custom (64-bit) | [MSC v.1900 64 bit (AMD64)]

E MATHEMATICAL REPRESENTATION OF THE MODEL

E.1 LOCATING AIRPORT NODES WITHIN THE GRAPH NETWORK

The process goes as follows; both the latitude and longitude of the first airport are selected and the 'great circle' distances between the airport coordinates and each of the nodes present in the graph are to be calculated using the Haversine formula. The Haversine formula method calculates the shortest distance between two points on the surface of a sphere, measured along the surface of the sphere (Gade, 2010). The following mathematical representation describes the process:

A Set of airport coordinates, indexed by a ϵ A, with $A = 1, ..., n$

C Set of all nodes in graph, indexed by c ϵ C, with $C = 1, ..., n$

$$d_{ac} = 2r \arcsin \sqrt[2]{\sin^2\left(\frac{\phi_c - \phi_a}{2}\right) + \cos(\phi_a)\cos(\phi_c)\sin^2\left(\frac{\lambda_c - \lambda_a}{2}\right)} \quad (E.1)$$

$$I_a = \arg\min_x \{d_{ax} : x \epsilon C\} \quad (E.2)$$

Where d is the great circle distance between point a and c, r is the radius of the sphere (the earth in this context), ϕ_a and ϕ_c are the geographical latitudes in radians of points a and c, and λ_a and λ_c are the longitudes in radians of point a and c (Gade, 2010). I_a is the node identifier that's being determined which is calculated by finding the node identifier with the lowest d.

E.2 CALCULATING THE TRAVEL TIME ON EDGES

The travel speed can be converted by using the following equation:

$$v_{meters/minute} = v_{km/h} * \frac{1000}{60} \quad (E.3)$$

Where $v_{meters/minute}$ travel speed (either maximum allowed speed or average travel speed) in meters per minute. This is calculated by multiplying $v_{km/h}$ (the speed in kilometres per hour) with 1000 divided by 60, as there are 1000 meters in a kilometre and 60 minutes in an hour.

The following equation is used to determine the travel time for an edge:

$$t = \frac{l}{v_{meters/minute} * \frac{1}{1+e^{-10Q-0.5}}} \quad (E.4)$$

Where t is the travel time in minutes, $v_{meters/minue}$ is the speed in meters per minute from either the maximum allowed speed or the average speed and

Q is the road quality that is on a scale from 0 to 1. The length is divided by the speed multiplied by the impact factor of the road quality and the road quality itself. The impact of the road quality on the speed follows a sigmoid function (also known as an S-curve). The sigmoid function is assumed to represent the impact of the road quality.

E.3 CALCULATION OF THE EDGE BETWEENNESS CENTRALITY

To calculate the edge-betweenness centrality for each edge following equation is used:

$$c_B(v) = \sum_{s \in S, t \in T} \frac{\sigma(s,t|e)}{\sigma(s,t)} \tag{E.5}$$

Where S is the set of sources, T is the set of targets, $\sigma(s,t)$ is the number of shortest (s,t)-paths, and $\sigma(s,t|e)$ is the number of those paths passing through edge e (Brandes, 2008). The set of sources are the airport nodes identified earlier, the targets are all nodes in the graph network.

E.4 CALCULATING AIRPORT BETWEENNESS CENTRALITY

The equation used to compute the airport betweenness centrality is somewhat similar to Equation E.5 and is the formula that calculates the betweenness centrality of all nodes. This is the following equation:

$$c_B(v) = \sum_{s,t \in V} \frac{\sigma(s,t|v)}{\sigma(s,t)} \tag{E.6}$$

Where V is the set of nodes, $\sigma(s,t)$ is the number of shortest (s,t)-paths, and $\sigma(s,t|v)$ is the number of those paths passing through some node v other than s,t. If $s = t$, $\sigma(s,t) = 1$, and if $v \in s,t$, $\sigma(s,t|v) = 0$ (Brandes, 2008).

F MODEL VERIFICATION

Table F.1: Check-list of all the verified model behaviours

Model expectation	Verification status
When the location query is set on any location, the model produces the graph of that location that looks the same as the network in OpenStreetMap.	Confirmed
When the airport location query is set on one or more airport names/addresses, the coordinates that are imported correspond to the actual coordinates of this airport in Google Maps	Confirmed
The nearest node to the airport that's found, has coordinates that are the closest to the airport coordinates when using the Haversine formula.	Confirmed
The travel time for an edge becomes extremely large when the road quality is set to 0.	Confirmed
The travel time for an edge corresponds to the maximum allowed speed on that edge when the road quality is set to 1.	Confirmed
When the maximum allowed speed is set to 1000 km/h, and the road quality to 1, the travel time becomes very small. When an edge does not have the maximum speed attribute, the specified average speed is used in the travel time calculation	Confirmed
When the road quality is set to 1 and an edge has 2 lanes, the flow time is exactly half of the travel time.	Confirmed
The edge betweenness centrality corresponds with the number of shortest routes that pass through this edge.	Confirmed
The airport node betweenness centrality corresponds with the number of shortest routes that pass through the airports.	Confirmed
The largest radius has the largest subgraph the corresponds to this reachability.	Confirmed
Each of the smaller radii has subsequently smaller subgraphs that correspond to the reachability.	Confirmed
The found reachability corresponds approximately to what can be found in Google maps travel times.	Confirmed
The most important nodes and edges are located on the busiest roads of the location.	Confirmed

G MODEL CHOICES

Table G.1: Overview of all choices that can be made within the model

Input	Requirements
Query for location	Any existing location that is available in OpenStreetMap
Query for airport locations	Any existing airport names or addresses that are available in OpenStreetMap
Road quality	On a scale from 0 to 1 (default is 1)
Average speed	Any speed in kilometres per hour
Choice of routing method	Minimising travel time Minimising travel distance Maximising road capacity while minimising travel time
Reachability radii	Any sequence of numbers in either minutes or meters (depending on routing method)
Top list of most important nodes/edges	Any positive number

H IMPLEMENTATION PROCESS OF THE VISUALISATION

H.1 VISUALISING REACHABILITY OF THE REGION

The visualisation is set up step by step. First, the colour map is chosen, which can be any desired colour map that Matplotlib offers. In this case, the colour map 'bone' is selected, which is a sequential colour map. Then the node colours are determined by using a list comprehension returning the colour blue for every node that is an airport node and no colour for every node that isn't an airport node. After this, the node size is determined, as the airport nodes need to be easily recognizable. Again, a list comprehension is used to return a node size of 300 when a node is an airport node, and 0 in all other situations. Making only the airport nodes visible as a dot in the visualisation. For this visualisation, the edges do not get a specified layout initially.

The next step is that the graph network is projected to UTM zone so that the relative positions of nodes and edges are accordingly to an actual map of the area. This projection is conducted by using a function from OSMnx. When the projection is complete, the fully constructed graph network is plotted using the plot function from OSMnx. In this plot function, the list of node colours and node sizes as previously specified by list comprehensions can be inserted as a parameter of the function. Other parameters that can be adjusted are the size of the figure, the opacity of the edges, the colour of the edges and more. These parameters are left to their defaults for now. The graph of the street network is drawn into the figure.

To visualise the reachability within the specified radii, an iteration is done over the list of radii, starting at the highest value. The first radius that's taken is 40. Then 40 is taken as a radius while iterating over all specified airports. Then with radius 40 and the first airport node, a subgraph is created by creating an ego graph. In this ego graph, the graph network is specified, the airport node id of the first airport, the radius of 40 minutes, and the routing option that needs to be considered, which is the travel time. As a result, a subgraph is constructed that only consists of the nodes and edges that are within the reach of 40 minutes from the first airport. However, the subgraph will not be plotted. Only the nodes and the edges that exist within this subgraph are to be identified and need to be given a colour and a certain buffer so that they create a small area of this colour around themselves. The coordinates of the nodes in the subgraph are saved to a geodataframe with their id's and geometries. The edges are also taken from the subgraph placing them in a list with LineString geometries, connecting them to the previously identified nodes. Then both the edges and nodes are given a buffer which is specified as 75 for the node buffer and 150 for the edge buffer, this will make them visible in the visualisation later on. Then the geometries (including the buffer) of both the nodes and the edges are joined together and a polygon is created. This polygon is then given a colour based on what radius is used. In this case, the highest radius is used, so the highest colour in the colour scale is taken, and assigned to this polygon.

This is repeated for every airport for the same radius. When every airport is iterated over, a list of polygons is returned and is drawn into the figure. Now the same process starts for the next radius, which is 20, this radius has the next colour in the colour map. This repeats until all polygons are created for every radius for each airport. When the figure is almost complete, the shape of the administrative boundaries is drawn around the figure, to indicate the area of interest. The last step to complete the visualisation is to add a colour bar legend, explaining which radius value is represented by which colour.

H.2 VISUALISING ROAD QUALITY AND ROAD CRITICALITY

Visualising the road quality and the road criticality of the graph network of the city of Rotterdam, the first step that needs to be undertaken is to project the graph to UTM in Python. Then the node colours and sizes are set to none and zero, except for the airport nodes. The airport node colour is blue and the size is 400, and this is set by using a list comprehension iterating over all nodes in the graph.

Then the edge colours and sizes are to be set. The edge colour is associated with the road quality of the edge, and each road quality is associated with a specific colour on a colour scale from red, to yellow to green. A colour dictionary is created by making an array from 0 to 1 with steps of 0.1, giving each value a colour from the colour map 'RdYlGn' ascending. Then a list is created for each colour an edge should get, by making a list comprehension, iterating over all edges. Then the road quality of each edge is taken, rounded to 1 decimal, and then looked up in the dictionary, returning a colour from the specified colour scale. The edge sizes are based on the edge betweenness centrality. the quartile cut function of pandas is used to split the possible betweenness centralities into 5 quantiles. This results in 5 possible edge sizes that are based upon the edge betweenness in the graph.

Then the graph is drawn including the specified node colours and sizes, and the specified edge colours and sizes. Also, the z-order is set to 3, meaning that the nodes of the airports will appear above the edges, making them more easily visible. Just as in the previous visualisation, the shape of the administrative boundaries is drawn around the graph network and a colour bar legend is drawn to show what the meaning is of the different colours.

I IMPACT ASSESSMENTS OF DISASTERS

This appendix includes four assessments of natural disasters from which two are about hurricane Irma on St. Maarten and the other two about the earthquake in Papua New Guinea. These assessments support the case-studies on both disasters as described in Chapter 7. On the following pages the impact assessments are displayed.

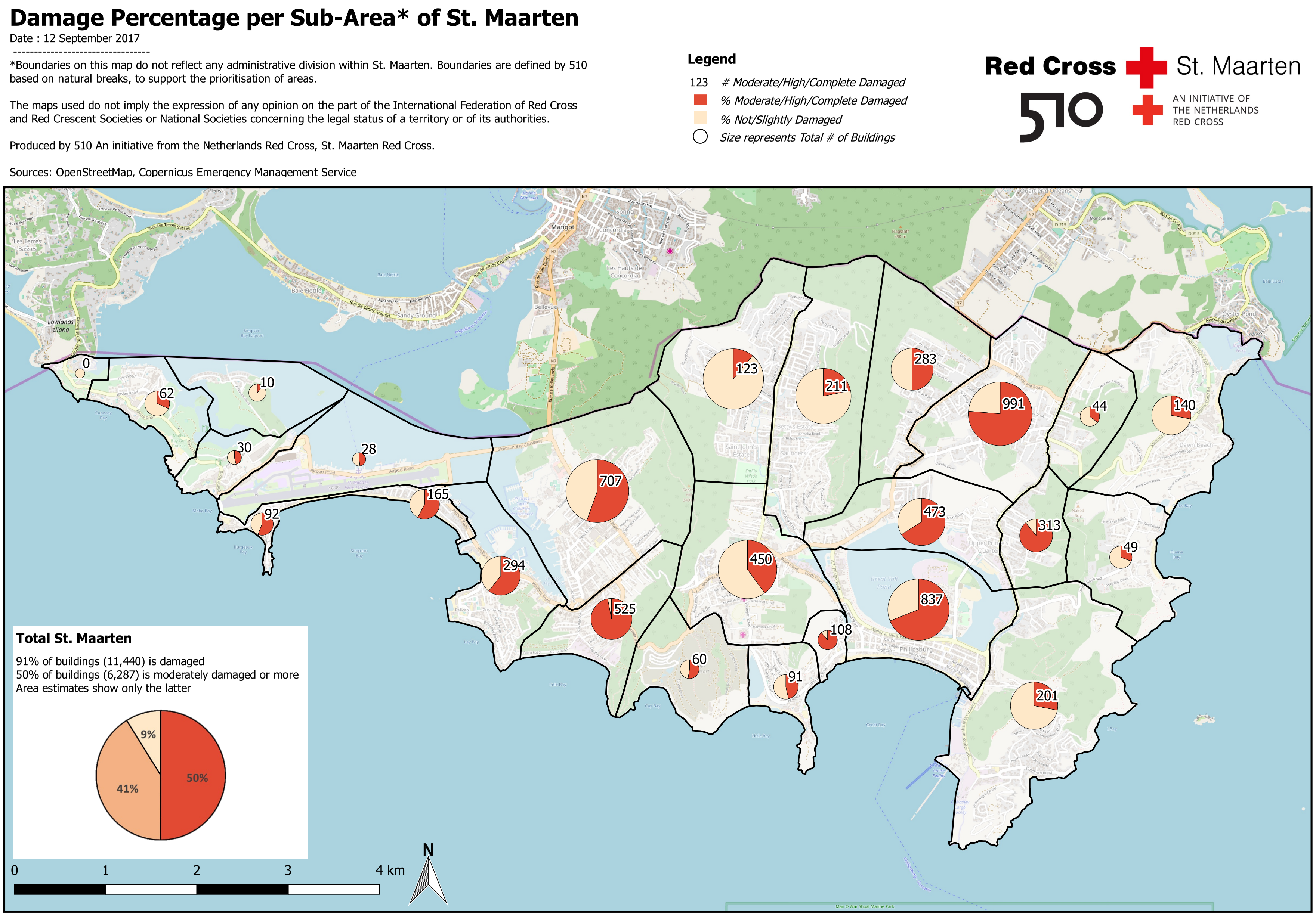


Figure I.1: Assessment map of destroyed buildings on St. Maarten after hurricane Irma (510 Red Cross, 2017b)

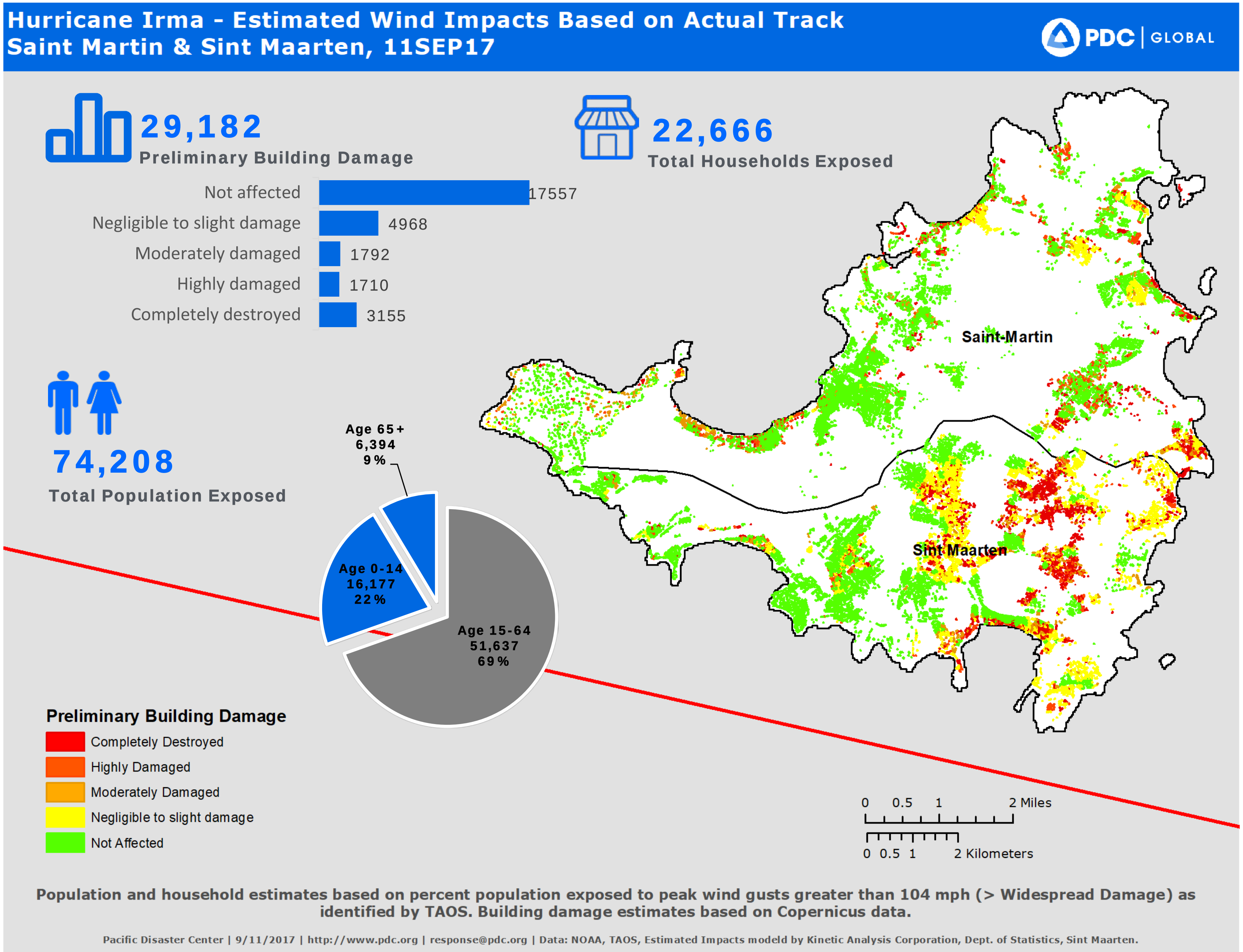


Figure I.2: Estimated impacts of hurricane Irma on St. Maarten (Pacific Disaster Center, 2017)

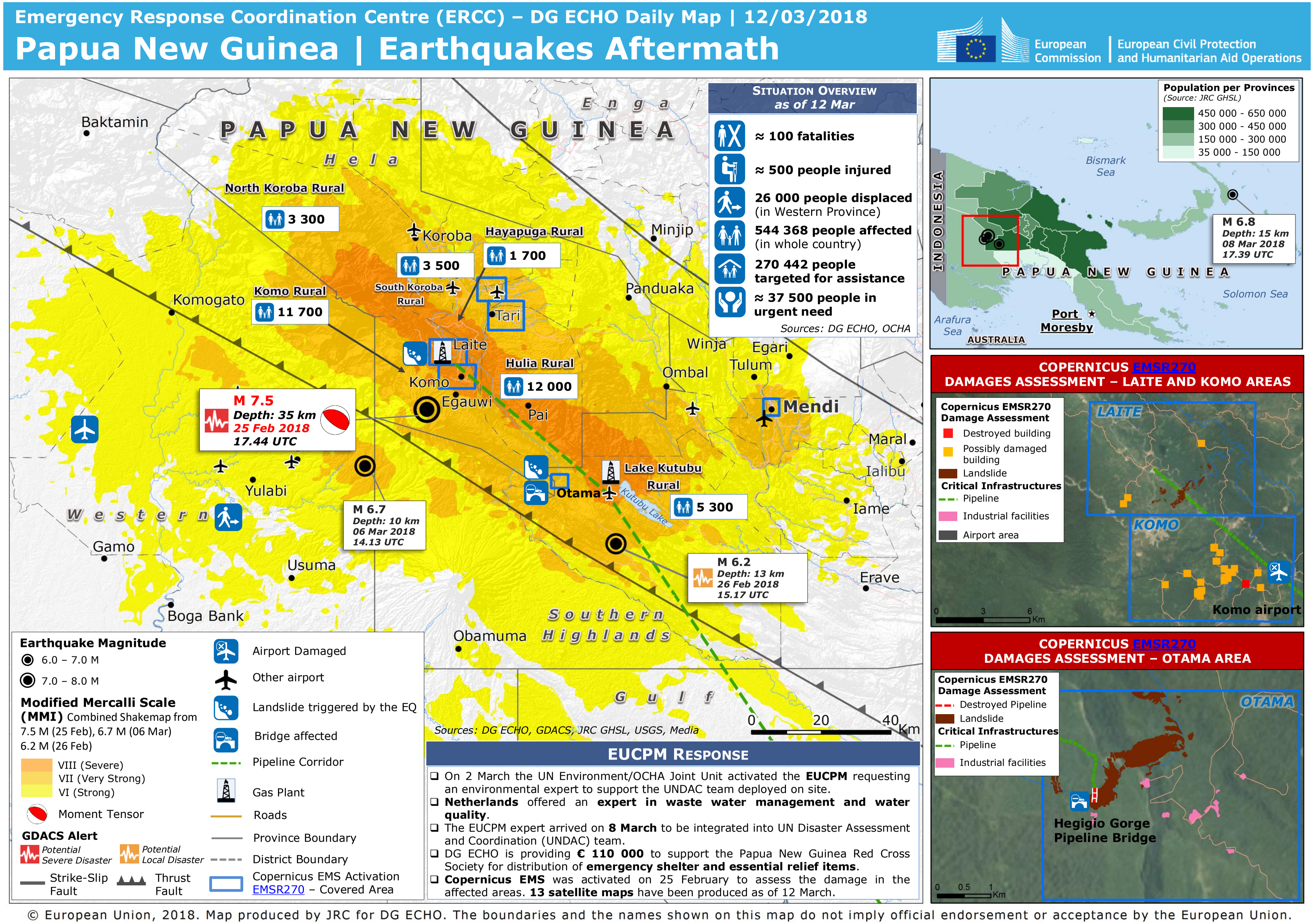
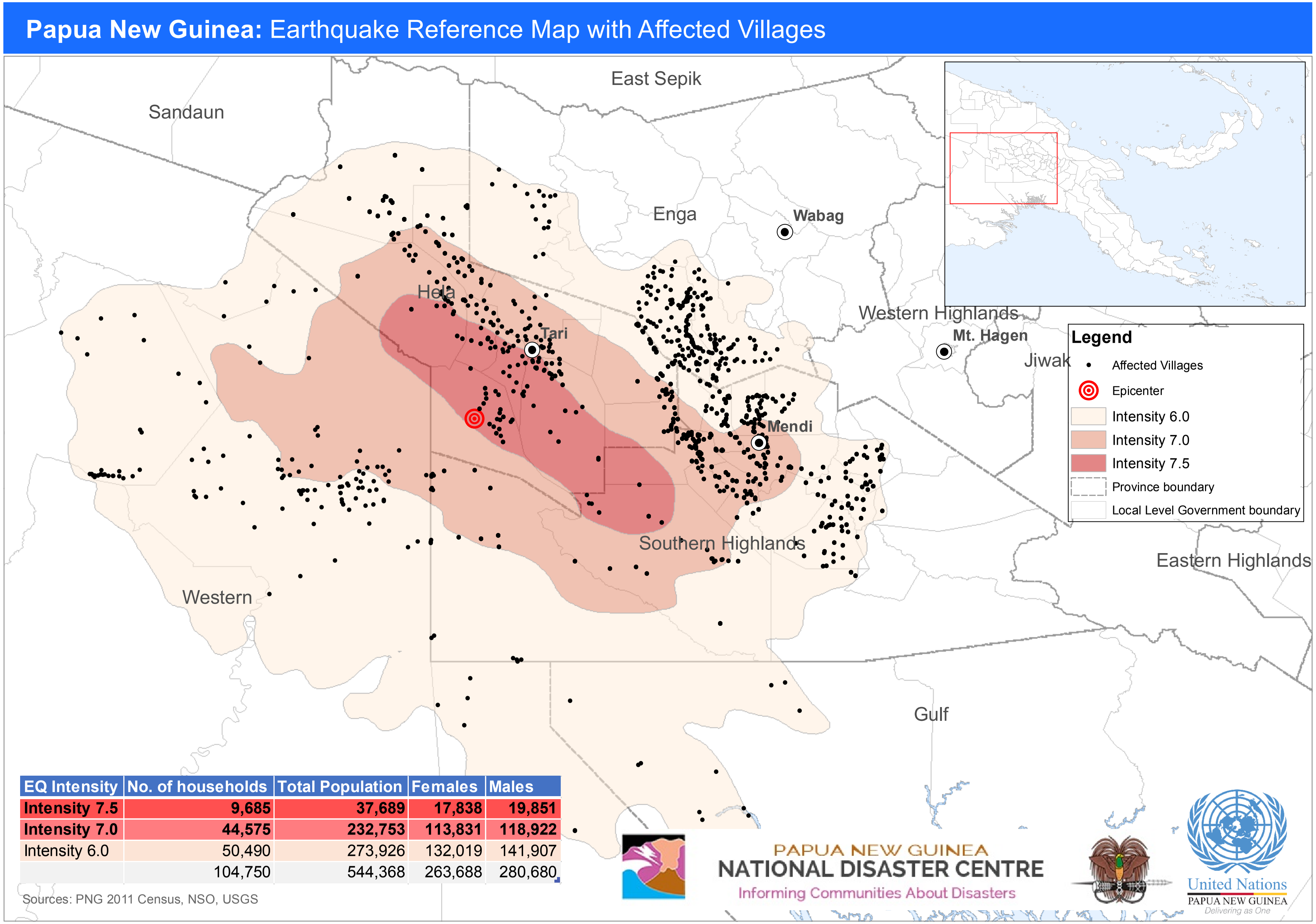


Figure I.3: Situational overview of the earthquake aftermath in Papua New Guinea (European Union, 2018)



EQ Intensity	No. of households	Total Population	Females	Males
Intensity 7.5	9,685	37,689	17,838	19,851
Intensity 7.0	44,575	232,753	113,831	118,922
Intensity 6.0	50,490	273,926	132,019	141,907
	104,750	544,368	263,688	280,680

Figure I.4: Map of villages affected by the earthquake of Papua New Guinea United Nations Papua New Guinea, 2018

J EXPERT INTERVIEWS FOR MODEL EVALUATION

For the evaluation of the model in addition to the case-studies, field experts are consulted and interviewed to explore whether the model could support decision-making and what important limitations of the model are. Two experts have been approached to conduct a semi-structured interview with. The questions that have been asked and the answers received on these questions are written down in this appendix. The interviews have been held in Dutch, therefore they're also written out in Dutch.

J.1 INTERVIEW 1: UNDAC LEAD OF OPERATIONS

The first interviewee is a lead of operations of UNDAC (United Nations Disaster Assessment and Coordination) and has been involved in the response during the disaster on Sint Maarten caused by hurricane Irma and many other disasters in the past years.

Bent u betrokken geweest bij Irma op Sint Maarten of de reddingsoperaties in Papua Nieuw Guinea na de aardbeving in februari?
Ik ben betrokken geweest bij heel veel rampen in de afgelopen jaren. Als lid van UNDAC behoor ik tot de eerste responders op een humanitaire ramp. Ik ben meermaals opgeroepen om hulp te geven bij rampen veroorzaakt door orkanen, modderstromen, aardbevingen, overstroming en meer.

Ik ben niet betrokken geweest bij de reddingsoperaties in Papua New Guinea na de aardbeving dit jaar. Wel ben ik betrokken geweest bij de humanitaire ramp op Sint Maarten als gevolg van orkaan Irma. De toegang tot Sint Maarten was problematisch omdat zowel het Princess Juliana vliegveld en de haven Dock Maarten beiden ernstig beschadigd waren door de orkaan. Na 5 dagen was het vliegveld enigszins hersteld, maar er mocht alleen maar op gevlogen worden door militaire vliegtuigen.

Wat zijn volgens u de belangrijkste besluiten die gemaakt moeten worden tijdens reddingsoperaties?
Als er ergens een ramp plaatsvindt, dan roep ik mijn team bijeen, waarop er een beeldvorming van de rampsituatie volgt. Deze beeldvorming wordt geanalyseerd en daaropvolgend neem ik met mijn team een besluit. Dan gaan we aan de slag en daarna wordt dit proces geëvalueerd om te bepalen waar we staan na de eerste operaties. Dit kent doorgaans een snelle doorlooptijd.

Welke problemen bent u tegen het lijf gelopen die gerelateerd zijn aan informatievoorzieningen?
Een van de belangrijkste dingen is dat de informatievoorziening snel is. Hoe eerder er een beeld van de situatie gevormd kan worden hoe sneller de op-

eraties van start kunnen.

Zou volgens u deze methode potentie hebben om besluitvorming tijdens reddingsoperaties te ondersteunen?
Ik denk dat jouw model niet alleen in accuratesse toegevoegde waarde kan geven, maar ook met name de snelheid van het produceren van de informatie. Een dergelijk model kan goed helpen als je snel kan schakelen.

Zo ja, kunt u voorbeelden bedenken van besluiten die ondersteund kunnen worden?
Door systematisch informatie te beheren, kan er beter bepaald worden wie welke hulp zou moeten krijgen met welke prioriteit. Jouw model kan hier zeker voor gebruikt worden. Het model kan ook helpen om te inventariseren hoe opvangcentra tijdens rampen het best bereikt kunnen worden. Of om te bepalen waar huisartsenposten geplaatst kunnen worden in een regio.

Wat zijn volgens u de belangrijkste limitaties aan deze benadering?
Het model geeft geen inzicht in waar mensen zijn die in de problemen zitten en hoe dit zich verhoudt tot hun bereikbaarheid. Het zou nuttig kunnen zijn om mogelijke oplossingen te kunnen simuleren. Het model laat niet zien wat de reistijd is op basis van drukte i.v.m. alle toeristen die jaarlijks naar Sint Maarten komen. Dit zijn situaties die niet in het model te zien zijn die wel invloed hebben op de infrastructuur. Met name het includeren van humanitaire parameters in het model kan van toegevoegde waarde zijn.

J.2 INTERVIEW 2: DUTCH ROYAL NAVY – LOGISTICS LIAISON

The second interviewee is a logistics liaison, who works for the Dutch Ministry of Defense as an advisor and was involved with the disaster on Sint Maarten after hurricane Irma as a logistics liaison.

Bent u betrokken geweest bij Irma op Sint Maarten of de reddingsoperaties in Papua Nieuw Guinea na de aardbeving in februari?
Ik ben vanuit de Koninklijke Marine van Nederland uitgezonden geweest naar Sint Maarten om daar het logistieke proces in de haven van Sint Maarten te coördineren vanaf het schip Karel Doorman. Dit was in de haven Port Sint Maarten en ook deze haven had veel schade opgelopen tijdens de orkaan. Er lagen zeecontainers in het water die geruimd moesten worden voordat de Karel Doorman kon aanmeren. Ik ben niet betrokken geweest bij Papua Nieuw Guinea.

Wat zijn volgens u de belangrijkste besluiten die gemaakt moeten worden tijdens reddingsoperaties?
De besluiten die genomen moeten worden om te bepalen welke goederen waar heen moeten op het eiland en wat de prioriteit is voor de diverse goederen.

Welke problemen bent u tegen het lijf gelopen die gerelateerd zijn aan informatievoorzieningen?
Een van de grootste uitdagingen waar ik mee te maken kreeg was in kaart

brengen van welke goederen vanuit Nederland binnen kwamen en inventariseren voor wie op Sint Maarten welke lading bedoeld was. Het was mijn taak om de informatie om het logistieke proces heen duidelijk te krijgen. Vaak ontbrak deze informatie en moest dit uitgezocht worden.

Zou volgens u deze methode potentie hebben om besluitvorming tijdens reddingsoperaties te ondersteunen?
Ik denk dat de methode voor ons eerder "nice to have" dan "need to have" is, maar voor de first-responders zoals medische diensten is dit cruciaal. Het is nuttig om te kunnen vergelijken hoe de infrastructuur verschilt van voor de ramp met de infrastructuur na de ramp.

Zo ja, kunt u voorbeelden bedenken van besluiten die ondersteund kunnen worden?
Het zou bijvoorbeeld kunnen bijdragen aan het bepalen waar (medische) posten geplaatst kunnen worden om de onbereikbaarheid van een omgeving te compenseren. Een andere situatie waarin dit model nuttig kan zijn is in het vervoeren van kritieke patiënten waar de snelste route van groot belang is.

Wat zijn volgens u de belangrijkste limitaties aan deze benadering?
Het model laat niet zien wat de reistijd is in relatie tot verkeersdrukte. Op Sint Maarten is he vaak heel erg druk en het is belangrijk dat het model inzichten geeft die vooral de rampsituatie goed weergeeft en het moet zich onderscheiden van bereikbaarheid die het eiland normaliter heeft.

K INSTRUCTION MANUAL FOR USING THE REACHABILITY MODEL IN PRACTICE

In this appendix, the instruction manual for humanitarians in the field is described step by step. The instruction manual aims to guide the user to configure a reachability model for a specified area using the algorithms as designed in this research. The reachability model used three algorithms: (1) The initialisation algorithm, (2) the model update algorithm, and (3) the visualisation algorithm. To configure a reachability model, several parameters need to be specified before the algorithms are used. Also, this manual assumes that the algorithms are already loaded onto the user's device together with all necessary packages.

STEP 1: SPECIFY LOCATION-RELATED INFORMATION

The first important thing is specifying the location where the reachability model should be based upon. For example, when wanting to use New York City as a specified place, the input should be *"New York City, New York, United States of America"*. Being as specific as possible makes the query more accurate.

Next, the entry points of the network need to be specified as well. The number of entry points up to the user's preference, it can be any number. The input should be inserted at once. For example, let's take LaGuardia Airport, John F. Kennedy Airport and Staten Island Ferry Whitehall Terminal as entry points, two airports and one harbour. This would then need to be defined as follows: [*"LaGuardia Airport, New York City, United States of America"*, *"John F. Kennedy International Airport, New York City, United States of America"*, *"Staten Island Ferry Whitehall Terminal, New York City, United States of America"*]

STEP 2: CHOOSE ROUTING OPTION

The next step is to determine the routing option that is used to define and calculate reachability. The user can choose from three routing options: (1) 'time', (2) 'length', and (3) 'flowtime'. When choosing 'time', the shortest travel time is used as a criterion when determining shortest routes. When choosing 'length', the shortest distance is used when determining the shortest routes. When using 'flowtime', the shortest travel time with the highest capacity is used when determining shortest routes.

When a routing option is chosen, the unit of the legend in the visualisation needs to be specified based on the routing type that is chosen. If 'time' is chosen, the unit of reachability is in *minutes*. If 'length' is chosen, the unit of reachability is in *meters*, and when 'flowtime' is chosen, the unit of reachability is in *minutes per volume unit*.

The average travel speed also needs to be determined. This is relevant when either 'time' or 'flowtime' is chosen as the routing option. The average travel speed needs to be determined for when there is no maximum speed information available for some edges in the network. The average speed that can be travelled depends on the vehicles used and the network, this is up to the user to determine.

STEP 3: DETERMINE REACHABILITY RADIUS

The third step involves determining the radii for which the reachability is preferred to be calculated. The radii are required to be specified as a list between brackets, with the routing type taken into consideration. The radii specified in this step, are in the unit as specified in the previous step. So, if 'length' is used as a criterion for the shortest route, the radii need to be specified in meters. For example, let's assume that 'time' is the reachability criterion, then the reachability radii may be specified as follows: [15, 30, 45, 60, 75, 90, 105, 120, 135, 150]. If these would be the specified radii, the reachability model would calculate the reachability up to two and a half hours with intervals of fifteen minutes.

STEP 4: SPECIFY FEATURES OF NETWORK

Before the graph is imported, some choices can be made to specify some features of the network. One feature is the network type, which determines which roads or paths are going to be imported. For this choice, the user needs to verify for what purpose the reachability model is going to be used. The different network types that can be used are the following:

- 'drive' - get drivable public streets (but not service roads)
- 'drive_service' - get drivable public streets, including service roads
- 'walk' - get all streets and paths that pedestrians can use (this network type ignores one-way directionality)
- 'bike' - get all streets and paths that cyclists can use
- 'all' - download all (non-private) OSM streets and paths
- 'all_private' - download all OSM streets and paths, including private-access ones

An important distinction here is the vehicle specific network types, which are helpful when the walkable, or cyclable reachability needs to be known. When all roads, streets and paths are to be included, 'all_private', is the best choice. The network type determines what roads are included in the import and if one-way roads exist or not.

Besides the network type, another network feature is whether the network should be simplified, or not simplified. A simplified network is a network where nodes that have no intersection are deleted. A simplified network takes less time to process but shows a lower distinction of reachability. This choice is up to the user and is also dependent on the size of the network.

STEP 5: DETERMINE THE VISUALISATION FEATURES

There are several visualisation features that may be adjusted to the preference of the user. The features are the colour map of the reachability radii, the node buffer, the edge buffer, the number of nodes or edges with the highest betweenness centrality displayed, the size of the nodes of the entry points, the size of the displayed nodes and edges with the highest betweenness centrality, and the edge size scale factor.

The default colour map is the one that is used in this research as can be seen in Chapter 6, which ranges from red to yellow to green. This colour map may be changed if preferred to any other colour map.

The node and edge buffer are used to create the field of the colour corresponding to a certain reachability around a node or an edge. This buffer size may be adjusted based on the size of the area that is explored. When an area is large, higher node and edge buffers are advised to increase the communicative potential of the reachability map.

The number of nodes or edges with the highest betweenness centrality displayed depends on how many critical roads and junctions the user wants to visualise. With larger networks, a higher number is advised. This number can be changed later on in the network.

The airport node size can be adjusted so that it can be distinguished in the visualisation. Again, the airport node size is dependent on the size of the network.

The size of the nodes with the highest betweenness centrality and the size of the edges with the highest betweenness centralities needs to be specified as well. It determines how large they will appear on the reachability map.

The edge size scale factor is 1 by default but could be increased with large networks to make the edges thicker to become more visible. This helps to distinguish the important edges from the less important edges, even in large networks.

STEP 6: INITIALISE THE REACHABILITY MODEL

When all parameters are specified, the initialisation algorithm can be run, using the specified parameters as input. This algorithm configures a graph of the network, a data frame with all geographic details of the network's boundaries, a list of the airports and an Excel file consisting of all the roads in the network, with ID's, road names, road lengths and road quality (set to

1). All these are stored on the local drive of the computer from which the algorithm is run.

STEP 7: VISUALISE THE REACHABILITY MODEL

When the data files of the network are configured and stored safely, the visualisation algorithm can be run using the parameters and the network data files as input. The algorithm creates five visualisations. The first displays the reachability of the different radii on the map. The second shows the road quality and betweenness centrality on the map. The last three are metaplots of the network, that show respectively, the airport betweenness centrality compared to the average betweenness centrality, the distribution of node betweenness centrality, and the distribution of edge betweenness centrality.

STEP 8: UPDATE THE REACHABILITY MODEL

When more information becomes available about changes in the network as a consequence of a sudden-onset disaster, the model can be updated to adjust to the actual state. Changes in the network could be roads that have become more difficult to cross or bridges that have collapsed, but also entry points that have become unusable, or other entry points to have become available.

The Excel file with all the data on the roads in it can be adjusted. When a certain road breaks down or is less accessible, this road can be looked up in the Excel file and the road quality value can be adjusted.

When the composition of entry points changes, this can be changed in the parameter of entry points as earlier specified in Step 1.

When all necessary adjustments are made, the model updating algorithm should be used. This algorithm takes the network information and recalculates the reachability based on the new information. When everything is recalculated, the new network data files overwrite the older files.

STEP 9: UPDATE THE REACHABILITY VISUALISATION

The updated reachability model needs to be visualised to match the changed situation by running the visualisation algorithm again. Five new visualisations are created and display the most recent view of reachability within the network.

Steps 8 and 9 can be repeated each time new information about the network comes in. If preferred, step 5 could also be repeated to adjust the parameters of the visualisation features.