



Developing and Evaluating a Pedestrian Navigation Tool for Earthquake Evacuation

GEO 511 Master's Thesis

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Abstract

This master's thesis develops and evaluates an earthquake evacuation navigation tool for the evacuation on foot of affected people immediately after an earthquake. While existing evacuation tools are predominantly designed for vehicle-based evacuation conducted by rescue workers hours to days after an earthquake, only limited research has addressed emergency tools for evacuees themselves in the critical phase of seconds to hours after the disaster. This thesis presents a proof of concept for such a GIS-based evacuation tool for the city of Zurich, Switzerland, and examines its decision-support potential. The tool is designed as a weighted network, whereby a multi-criteria evaluation is used to calculate the evacuation time per road section based on various contextual and environmental factors. Using Dijkstra's shortest path algorithm, optimal evacuation routes and destinations are determined by minimising evacuation time. The tool is evaluated by a survey that examines earthquake evacuation decision-making prior to introduction to the tool and subsequently after introduction. The survey results indicate that participants often consider factors such as proximity, social dynamics, familiarity or perceived risk when deciding on an evacuation site. More abstract, intangible factors are often overlooked. Following the introduction of the tool, participants describe it as helpful in increasing confidence and perceived safety. The findings suggest that earthquake evacuation tools have considerable potential to support decision-making, with the integration of human evacuation behaviour into evacuation modelling offering significant opportunities.

Keywords: earthquake evacuation, evacuation navigation tool, geographic information systems (GIS), multi-criteria evaluation, human evacuation behaviour, network-based evacuation modelling

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List of Acronyms

Acronym	Definition
DSM	Digital Surface Model
DTM	Digital Terrain Model
EENT	Earthquake Evacuation Navigation Tool
GIS	Geographic Information System
H	Hypothesis
MCE	Multi-Criteria Evaluation
RQ	Research Question

1 Introduction

1.1 Motivation

Large-scale environmental disasters impact thousands of people worldwide every day. Among these hazards, earthquakes are considered the most dangerous and destructive (Barone & Mocetti 2014, Morales-Esteban et al. 2010). More than half of all deaths caused by environmental catastrophes are due to earthquakes. In the past 20 years, this has amounted to approximately 750,000 deaths globally (WHO 2025). Moreover, earthquakes cause immense damage to infrastructure, resulting in an average annual cost of 20 billion Swiss francs over the past 10 years (Our World in Data 2025). A major reason of this is the unpredictability of earthquakes. Although research into earthquakes has been ongoing for many decades, where or when earthquakes strike, is still largely unknown (Kanamori & Brodsky 2004). Furthermore, earthquakes can trigger other environmental disasters such as floods, landslides or tsunamis, thereby making them an even greater threat (SED 2025a).

How people react after an earthquake is thus of immense importance, as the interaction between human behaviour and the environment in the aftermath of an earthquake is crucial in reducing unnecessary casualties (Shapira et al. 2018). Human-related aspects such as prioritising what to do or where to go to after a major disaster, as well as the chosen evacuation destination and its route may either increase or decrease the outcome of an earthquake (Sun et al. 2021). Since earthquakes are highly complex, it is challenging to remain rational and calm after experiencing one. Especially in densely populated urban areas, the public's lack of knowledge about appropriate evacuation procedures leads to a significant number of additional injuries and deaths (Sun et al. 2021).

Currently, evacuations after earthquakes mostly take place hours to days after the disaster, as organizing large-scale evacuations of thousands of people requires substantial coordination and the mobilization of extensive emergency personnel (Shimura & Yamamoto 2014). Such evacuations are typically carried out by emergency workers heading to the affected areas in vehicles to find people in need. Moreover, information on how to behave is shared online. However, this is a race against time, as the chances of survival after an earthquake decrease drastically as time passes (NAZ 2004). Thus, a rapid evacuation immediately after an earthquake could reduce the impact of casualties and injuries. To manage such evacuations, evacuation maps and navigation tools demonstrate great potential (Tsonas et al. 2016, Shimura & Yamamoto 2014).

The use of evacuation maps has become an increasingly prominent topic over the past 30 years (Southworth 1999, Chen & Cheng 2020). Currently, tools based on geographic information systems (GIS) are used to guide emergency responders in long-term evacuations following environmental disasters (Chen & Cheng 2020). These navigation tools are designed exclusively for rescue workers, who typically arrive hours or days after an earthquake. A convincing aspect of such GIS-based applications is their possibility of incorporating various spatial factors such as road network capacity or the spatial distribution of the population (Southworth 1999). These applications also include dynamic components, as population density and traffic capacities are constantly changing. This leads to changes in the calculated routes depending on the current spatial situation (Southworth 1999). Although GIS-based evacuation tools supporting emergency responders are well established, only little research has been made on how such navigation tools could be modified to be used by the common people that are affected by an earthquake (Tsionas et al. 2016, Shimura & Yamamoto 2014). Earthquake navigation apps, which the affected population could use on their own mobile devices, have, to date, not been developed. Such apps would be used for evacuation on foot, as motorized evacuation is strongly discouraged right after an earthquake and is often impossible due to debris on the roads, blocked routes and unsafe infrastructure (Shimura & Yamamoto 2014). These navigation apps hold a great potential for evacuations to be carried out much more rapidly and in a more organized manner, thereby preventing unnecessary casualties (Sun et al. 2021). This is due to people being less likely to panic, which would reduce the chances of them going to areas where there is a high risk of buildings collapsing. Moreover, such a tool could help in identify the safest evacuation routes and sites, therefore supporting evacuees to reach designated areas more efficiently and receive medical assistance more quickly (Sun et al. 2021).

Thus, in the scope of this master thesis a prototype of a navigation tool will be developed, which guides people affected by an earthquake to an evacuation site using optimised pedestrian evacuation routes. This tool will be based on the current state of research and will combine various approaches into a comprehensive tool. The tool will be limited to the city of Zurich, Switzerland, and will only be available as a proof of concept in Python code. The developed tool is then evaluated in the form of a survey on its perceived helpfulness and functionality. Consequently, the aim of this thesis is to find out if and how a navigation evacuation tool can support people affected by earthquakes in their decision-making process and what kind of opportunities such a tool offers.

1.2 Objectives

This thesis has two main objectives: developing an earthquake evacuation navigation tool and evaluating the tool through a survey. In the following sections, both objectives are explained in more detail.

1.2.1 Earthquake Evacuation Navigation Tool

An earthquake evacuation navigation tool (EENT for short) is a tool intended to guide people on foot to an evacuation site in an optimal manner immediately after an earthquake. There are several approaches in research on how such tools can be programmed, but the research field is still evolving, with no established state of the art yet (Ye et al. 2011, Tsionas et al. 2016, Shimura & Yamamoto 2014). In the scope of this thesis, different methods for the development of an EENT will be analysed, which will serve as a basis to program a tool that combines various aspects of these approaches. The result will be a tool in the form of Python code, where users enter their location, the strength of the earthquake and whether it is day or night. They can also choose if they want to be guided to the most optimal evacuation site, a hospital or a custom destination point. The tool then calculates the best destination (if no custom point has been selected) and the best route to reach it based on various factors and visualises this on a map.

The tool is spatially limited to the city of Zurich. Since it is intended as a general proof of concept, the geographical location is not the focus of the tool. Zurich was primarily chosen due to the data availability and the author's familiarity with the city. Additionally, in the evaluation of the tool the influence of spatial knowledge will be examined, which is why a location had to be chosen where enough participants could be found who were familiar with the study location. Moreover, the spatial extent of the prototype should also cover extensive infrastructure and bodies of water in order to examine different effects of an earthquake, which Zurich can provide. It should also be emphasised that although Zurich, and Switzerland in general, are not severely affected by earthquakes, earthquakes with a magnitude of six or more occur every 50 to 150 years in Switzerland (SED 2025b). The last of these major earthquakes occurred around 80 years ago, highlighting that the likelihood of a significant earthquake happening in Switzerland should not be disregarded (SED 2025b).

1.2.2 Survey

The second objective of this thesis is to evaluate the developed EENT in the form of a survey. For this, the survey will first test the participants decision-making process in a hypothetical

earthquake evacuation situation before being introduced to the tool. To do this, participants must perform a task in which they are placed in a situation where an earthquake has struck Zurich and they must explain how they would react and where they would evacuate to. After this task, participants are introduced to the EENT and are explained how this tool would choose an evacuation site. Participants then answer questions about the perceived helpfulness, functionality and shortcomings of the tool. Ultimately, the survey aims to assess if the EENT has the potential to support users in their decision-making process during an earthquake evacuation situation.

1.3 Research Questions and Structure

This thesis aims to answer the following three research questions:

RQ1: How can earthquake evacuation navigation tools model the complexity of an earthquake and its impact?

RQ2: How can earthquake evacuation navigation tools determine optimal evacuation destinations and routes?

RQ3: How can earthquake evacuation navigation tools support users in evacuation decision-making?

Research questions one and two are explored in the development of the EENT by reviewing relevant literature and creating a methodological framework for building the tool. Research question three is explored in the survey and supported by statistical analysis. While no hypotheses can be formulated for research questions one and two, as they are exploratory in nature and are assessed through the process of developing the EENT, three hypotheses are formulated for research question three, as it involves the collection of empirical data and the analysis of possible relationships. Thus, the following hypotheses are presented:

H1: Participants generally select the spatially closest evacuation site.

H2: Participants with higher local knowledge are more likely to select an evacuation site they are familiar with.

H3: Participants with higher earthquake knowledge are more likely to select the same evacuation site as the one calculated by the EENT.

The remainder of the thesis is structured as follows: Chapter 2 presents the state of the art on human behaviour in evacuation situations, the research field of earthquake evacuation maps and models, and existing gaps in research. Chapter 3 outlines the methods used for both the development of the EENT and the survey, and Chapter 4 presents the corresponding results. Chapter 5 discusses the results in relation to current research, and Chapter 6 summarises the findings of this thesis in a conclusion. The work ends with an appendix containing the entire survey.

2 State of the Art

The state of the art first provides an overview of the current research on human behaviour in earthquake evacuation situations. It examines the specific characteristics of earthquake evacuations, as well as the cognitive decision-making process and its key factors in literature. Subsequently, the state of research on earthquake evacuation mapping and digital tools is discussed, with a focus on evacuation tools for affected people. Various methods and influencing factors underlying these tools are analysed. Finally, research gaps within the fields of study are presented, and the positioning of this thesis within these gaps is outlined.

2.1 Human Earthquake Evacuation Behaviour

The behaviour of people during earthquake evacuations is a broad and complex topic. Earthquakes are extreme events that people do not encounter in their normal lives. They lead to high-stress situations in which many decisions must be made in a matter of moments (Mohajeri & Mirbaha 2021). Understanding human behaviour and this decision-making process is of great importance in developing appropriate evacuation measures (Blake et al. 2022).

2.1.1 Earthquakes as Evacuation Scenarios

Earthquakes are the most destructive environmental disaster to exist, which is why the evacuation process following one is a major challenge (Morales-Esteban et al. 2010). Since earthquakes occur without a warning and the peak of destruction is reached within a few minutes, the affected area quickly descends into chaos (NAZ 2004). This sudden event results in a drastic disruption of infrastructure, mobility and communication across a large area. Operational resources for deploying emergency personnel are also severely affected, resulting in a highly uncoordinated response in the initial phase after an earthquake (NAZ 2004). As described in Switzerland's emergency protocol (NAZ 2004), an earthquake quickly overwhelms the government's capabilities, which is why the first few hours after such a disaster are defined as the chaos phase, where resources and emergency workers must be mobilized from other locations. During this chaotic phase, affected people are largely left to rely on themselves. However, these first few hours are also the most important phase for the survival chances of those affected, due to the risk of infrastructure collapse and sustained injuries during the event (Ahmadi et al. 2025). For this reason, the evacuation and rescue of individuals from the affected area is a time-critical task. The faster the evacuation, the greater the chances of mitigating the effects of the disaster (NAZ 2004).

Moreover, urban settings prove to be particularly vulnerable to earthquakes compared to smaller or rural areas (Shapira et al. 2018). Due to the large amount of infrastructure and high population density, the space to evacuate is limited. Streets become overcrowded more quickly and have higher chances of being blocked by debris from collapsed buildings (Shapira et al. 2018). Thus, the chaos phase following an earthquake is even more uncontrollable and dangerous in such locations.

After a few hours, it is expected that emergency responders will have been mobilised and that the evacuation of those affected can begin. Attempts will be made to restore communication channels to share important behavioural information with the population (NAZ 2004). While a coordinated response can be organised at this stage, in the first few hours support, leadership and information are lacking.

2.1.2 Decision-Making Process in Evacuation Situations

The population plays an active role after an earthquake. As there is a lack of systematic leadership in the initial phase, affected people must mainly decide for themselves how to respond (NAZ 2004). During this chaos phase, people experience great shock and fear (Blake et al. 2022). The event can only be processed cognitively to a limited extent due to the immense amount of information and changes that occur within a very short time. The initial reaction when an earthquake is felt is for approximately half of the affected people to seek cover under a sturdy object such as a table or doorframe and for the other half to attempt to move outdoors or to an open area if they are already outside (Blake et al. 2022, Shapira et al. 2018). After this reaction, people experience acute stress and fall into a state of panic due to the sudden loss of control. This influences their decision-making processes and can lead to temporary irrational behaviour and compromised judgement (Blake et al. 2022, Sun et al. 2021). While this state of panic can alter behaviours, it does not mean that people act completely uncontrollably. Templeton et al. (2023) and Drury et al. (2023) argue that acute high panic is typically a brief reaction, followed by a goal-oriented behaviour. While panic may continue to influence behaviour, individuals remain capable of making meaningful decisions aiming to restore a sense of security. Giddens (1991) argues that humans always strive for a state of security. This describes a state in which one feels safe and has a sense of order. People consistently try to understand their environment, which drives their behaviour. This desire for security leads people to consciously seek a path to safety after a large-scale disaster, which ultimately shapes their decision-making process in the subsequent evacuation situation (Giddens 1991).

Mohajeri & Mirbaha (2021) describe this decision-making process in the event of a high-stress evacuation as a four-step procedure consisting of: (1) if a person decides to evacuate, (2) how they plan to evacuate, (3) where they intend to go, and (4) which route they will take. In the first step, the decision for or against evacuation is made, with people opting for evacuation in most cases (Mohajeri & Mirbaha 2021). Few people decide against evacuation for medical reasons or social bonds, by, for example, deciding to stay with family members who are unable to move (Templeton et al. 2023). In the second step, people decide on the mode of evacuation, primarily choosing their means of transportation. In earthquake situations, evacuations tend to be on foot, as roads are unstable or covered with debris making them inaccessible to motorized vehicles (SED 2025b). In the third step, evacuees decide on their evacuation destination. Most people either head for open spaces such as fields or parks, hospitals in the event of injury, or the homes of friends and family (Shapira et al. 2018). In the final step, people choose the route they will take to get there. This route is often decided on or changed while a person is traveling to their destination based on various social or environmental factors (Mohajeri & Mirbaha 2021). Figure 1 displays an overview of this decision-making process.

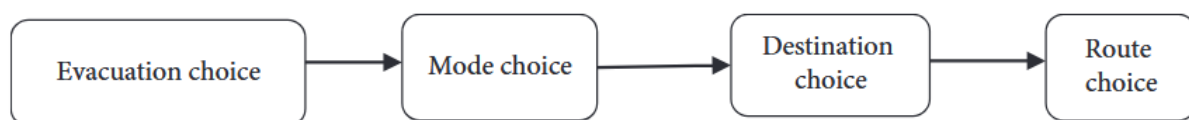


Figure 1: Human evacuation decision-making process in large scale environmental disasters

2.1.3 Factors Influencing Evacuation Behaviour

The choices made in the decision-making process are influenced by various demographic, psychological, social, and environmental or contextual factors (Mohajeri & Mirbaha 2021).

Demographic Factors

Mohajeri & Mirbaha (2021) found that demographic factors such as age, gender, income, religion or family status influence how people respond in evacuations. They discovered that the probability of evacuating after an earthquake is higher for married individuals and individuals with more family members. They also found that women tend to evacuate more quickly as they perceive risk sooner and may be more inclined to help others. Moreover, Mohajeri & Mirbaha (2021) identified a trend that younger people are more likely to choose to evacuate rather than elderly people. Specifically, the groups of 18–24 and 25–32 year-olds tend to decide earlier to evacuate their building. These results are supported by Bateman & Edwards (2002), who found

that women are more likely to evacuate than men in disasters as they feel more quickly at risk or feel responsible for protecting children. Furthermore, Yun & Hamada (2015) learned by conducting a survey after the 2011 Tohoku-Oki earthquake in Japan that age and occupation displayed the biggest influence on evacuation behaviour. Blake et al. (2022) found similar results by conducting a survey after the 2016 Kaikoura earthquake in New Zealand that age, socio-economic status and ethnicity were important driving factors in the decision to evacuate. In a virtually based experiment by Ahmadi et al. (2025), where participants had to decide how to respond to an earthquake in a simulated environment, demographic, cultural, and socio-economic characteristics were also found to be influential factors. Moreover, Whitehead et al. (2001) as well as Yang et al. (2016) also explored the influence of these demographic factors on hurricane evacuations and found that especially age, income, education and gender displayed the most prominent influence. Thus, overall, various sociodemographic factors can influence the evacuation behaviour with the key factors being age and education, as they are identified across all reviewed literature.

Psychological Factors

Other aspects which exhibit a relationship with decision-making in evacuation situations are psychological factors. Former experiences with evacuation situations as well as personal risk perception can influence if and how individuals decide to evacuate (Eiser et al. 2012). Xie & Xu (1995) describe that intuitive judgement and subjective feelings are an important part of risk perception. In high-stress decision-making situations, this personal assessment of risk plays a major role. Furthermore, Shapira et al. (2018) conducted a survey with people residing in high-risk earthquake zones in Israel and investigated how these people would react during an earthquake. As a result, they proposed the “Protection Motivation Theory”, which states that people engage in self-protection mainly based on how severely they perceive a risk and how they evaluate their resources for dealing with the disaster.

Social Factors

In addition, social factors and group dynamics have a significant influence on evacuation decision-making (Ahmadi et al. 2025). Templeton et al. (2023) propose three main social behaviours: (1) Following Behaviour, (2) Crowd Behaviour, and (3) Social Bonds Behaviour. The Following Behaviour describes a response of individuals to follow an authority figure. These can be people they happen to encounter at random or official leadership figures such as the government or rescue teams (Templeton et al. 2023). The Crowd Behaviour describes the tendency of people to seek out and follow groups of people. Individuals usually gravitate towards

the centre of crowds and move in herds in high-stress situations (Templeton et al. 2023). Finally, the Social Bonds Behaviour indicates that affected individuals attempt to contact or find significant close people, such as family members or loved ones during evacuation situations. Besides Templeton et al. (2023), Shapira et al. (2018) found that individuals are more likely to seek out the proximity of a familiar person rather than evacuate to an official safe place after an earthquake. In addition, Lin et al. (2020) found a strong relationship between social bonds and evacuation behaviour as well. While conducting a virtual reality experiment about major fire evacuations, they determined that people tend to follow crowds or people with leader characteristics rather than acting alone. Moreover, Drury et al. (2023) found that people tend to gather in groups with the same demographic characteristics, such as ethnicity or age and Zhang & He (2022) found that in evacuation situations happening at night, this urge to form groups is even stronger. This can be attributed to the fact that being in a group can reduce the feelings of disorientation and loss of control, which are even greater at night in the dark. In general, during nighttime evacuations the drive for social contact is the main factor influencing the decision-making process (Zhang & He 2022).

Another key social factor to consider is the instinct to help other people in earthquake situations. Ahmadi et al. (2025) as well as Templeton et al. (2018) both describe that altruistic behaviour is highly common in evacuation situations. This describes voluntarily searching for and helping injured people instead of first securing one's own safety. Furthermore, Ntontis et al. (2018) found that this altruistic behaviour is prevalent in all large-scale disasters and involves both physical assistance and emotional support.

Environmental and Contextual Factors

Finally, environmental and contextual factors also significantly impact the choice of evacuation. Decisions are influenced by the immediate environmental conditions following an earthquake, such as the debris on roads, structural damage and natural factors (Templeton et al. 2023). The perception of risk comes into play here as well, as different people may classify these environmental impacts as varying degrees of risk (Shapira et al. 2018). For example, natural elements such as bodies of water or green spaces may help or hinder an evacuation, depending on the perception of the person (Templeton et al. 2023). Familiarity with the area is also crucial. Various papers such as Sun et al. (2021), Zhang & He (2022) and Tai et al. (2014) found that in earthquake evacuations affected people tend to choose evacuation routes and destination they are familiar with.

In addition, the time of the day can impact evacuation behaviour. Zhang & He (2022) discovered that if an earthquake strikes at night, people are more likely to evacuate in groups, opt for routes and destinations with increased lighting as well as head to locations they are more familiar with than they would have if the earthquake would have happened during daytime.

Lastly, evacuees often also take the distance to their destination into account, as they want to reach their target location as quickly as possible (Sun et al. 2021). According to Bañgate et al. (2019) people in evacuation situation try to opt for the shortest route to their destination. In addition, the size of the evacuation site has an influence as well, with larger destinations often being preferred as they can accommodate more people and thus do not easily become overcrowded (Bañgate et al. 2019).

2.2 Earthquake Evacuation Mapping

In order to support affected people during evacuations after an earthquake, various approaches for assistance systems such as maps and digital tools have been introduced in recent years. The research field of earthquake evacuation mapping has evolved dynamically over the past 30 years, producing many new methods and concepts (Chen & Cheng 2020). The following sub-chapters describe this development and how it has progressed to its current state.

2.2.1 Dynamic and Network-Based Evacuation Mapping

Until the 1990s, evacuation maps were mainly established as static maps, showing the best route out of buildings in small-scale emergencies. For large-scale evacuations following environmental disasters, no such evacuation maps existed (Coppock 1995). Then, the 1990s saw a surge in research into evacuation maps in the event of major disasters. As one of the pioneers of large-scale evacuation mapping, Southworth (1991) introduced the topic of evacuation aids in the form of dynamic maps in 1991. He argues that in major emergency situations, evacuations by vehicles can be improved with the help of maps. Southworth (1991) describes how people's behaviour in evacuation situations often leads to traffic jams and poor use of the road network. As a result, the evacuation process is much slower and less efficient than it could be with an organised structure. To address this issue, Southworth (1991) proposed the concept of dynamic street maps, which display the location of all people in a road network and indicate areas of congestion or open roads. These maps change dynamically depending on the distribution of people. Based on this information, evacuees can then take the route to their evacuation site with the shortest distance or time. Furthermore, he argues that these dynamic street maps should operate according to a network principle. The street system is represented as a network, where

junctions are nodes and road sections in between nodes are edges (see Figure 2). After a disaster, the capacity of edges in a network can be calculated based on the vehicle density and stored as an attribute on the corresponding edge. In this way, the street network is conceptualised as a weighted graph in which edge weights represent their capacity (Southworth 1991).

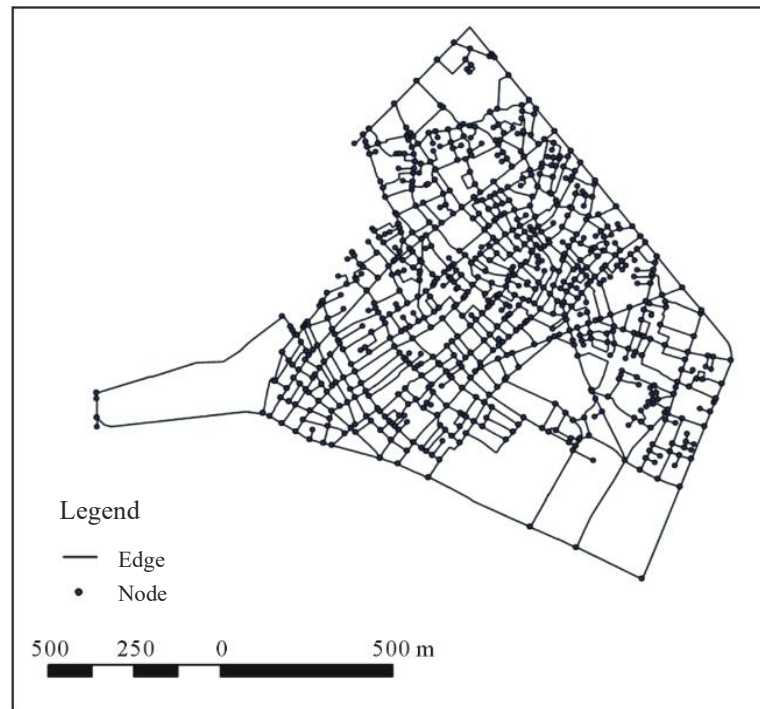


Figure 2: Road network represented as a network of edges and nodes for dynamic calculation of road capacity, Tokyo, Japan (Shimura & Yamamoto 2014)

Moreover, it is essential that a distinction is made between the daytime and nighttime population in these dynamic maps. Glickman (1987) notes that a population is divided into three types of populations: the at-home-population, the at-work-population and the at-school-population, all of which exhibit different spatial distributions. The size of these populations fluctuates depending on the time of day. For a successful evacuation route, it is necessary to evaluate which population group the individuals are in at that time, to determine the populations spatial distribution (Southworth 1991). While Southworth (1991) had focused solely on the population distribution and capacity of roads, Cova (1999) further argued that the effects of the disaster itself on the road network must also be considered. He argues that large-scale disasters must be identified as a hazard source which pose a risk to damage infrastructure. Thereby, Cova (1999) established a key formula for evacuation mapping: The risk of damage to infrastructure is determined by the hazard, consisting of its characteristics and strength, and the vulnerability of the infrastructure itself, such as its structural integrity and type of construction (see Figure 3). While the nature and severity of a possible hazard itself are mostly unpredictable, the

vulnerability of infrastructure to different hazards can be assessed to a certain extent. Thus, an essential addition to evacuation mapping is the vulnerability of streets or infrastructure, as structural damage to these may affect the accessibility of the road network by restricting or blocking routes completely (Cova 1999). By collecting spatial characteristics of infrastructure such as distributions or densities as well as properties such as type or age, assumptions can be made as to how the infrastructure might react in the event of a disaster. This vulnerability data can then be visualised on maps to spatially show how vulnerable areas are to various hazards. This concept is called evacuation vulnerability mapping and is considered central to identifying evacuation routes (Cova 1999). Thereby, in connection with the network model proposed by Southworth (1991), additional vulnerability factors can be added to edges in a road network, thus broadening the information and help provided by these evacuation maps. This allows the distribution of the population in the road network as well as the effects of the disaster itself to be illustrated on a single map (Cova 1999).

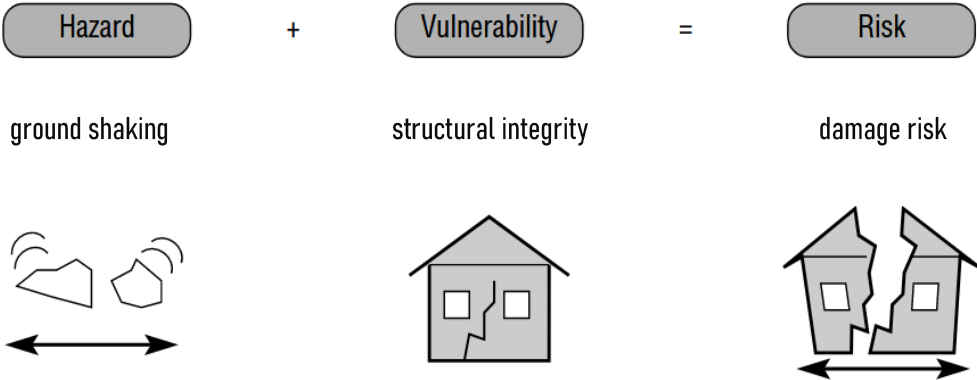


Figure 3: Disaster collapse risk formula (Cova 1999)

For the development of such evacuation maps, GIS proved to be an essential tool (Chen et al. 2008). GIS are systems used to capture, manipulate, process, store and display spatial data. They can handle various types of geographical data and perform spatial functions with it (Bo et al. 2009). This includes both geometric data such as coordinates or geometry types, and descriptive attribute data, for example building type or year of construction (Bo et al. 2009). By using GIS, various spatial data layers for evacuation vulnerability, such as debris from demolished buildings or destroyed roads like collapsed bridges, can be overlaid, enabling the generation of a comprehensive map. This visualisation of vulnerability helps to identify and understand patterns for evacuations, thereby supporting spatial decision-making (Chen et al. 2008).

2.2.2 Evacuation Tools for Rescue Workers

Based on these network and vulnerability evacuation maps, various tool-based approaches to support rescue workers in long-term evacuations were discussed in the following years. In this context, *long-term evacuation* refers to evacuations happening hours to days after a catastrophe, involving the use of rescue vehicles. Jotshi et al. (2009) proposed one of the first methodologies for an evacuation navigation model that dynamically supports rescue workers in evacuations after large-scale disasters such as earthquakes. They created a network model that determines optimal routes for emergency vehicles based on the location of people, traffic density and the condition of the roads. These routes change dynamically and display the fastest way to a destination, which is mostly large crowds of affected people or hospitals (Jotshi et al. 2009). This works by using Dijkstra's shortest path algorithm. Dijkstra's shortest path algorithm is an essential method in navigation research, as it allows the shortest path between one or more points in a network to be determined (Dijkstra 1959). The algorithm computes all possible paths between a starting node and all other nodes and selects the path that has the shortest length of edges in total (Dijkstra 1959). In the model by Jotshi et al. (2009), Dijkstra's algorithm is used in that instead of the length of edges, the time it takes to travel through the edges is used. For this purpose, each edge is assigned a level of damage which indicates how severely an edge is blocked by damage to roads, debris from buildings or other obstacles, thus displaying the hazard vulnerability per edge. The higher the damage level, the longer it takes to traverse that edge. An edge with a damage level of 100% means that the entire edge is blocked and is therefore marked as impassable. In addition, a high density of emergency vehicles on an edge can also increase the time to pass through it, as this can cause traffic jams (Jotshi et al. 2009). Based on the evacuation time per edge by using Dijkstra's shortest path algorithm the fastest evacuation route is determined. Furthermore, Jotshi et al. (2009) argue that the use of live data could optimize the model even more. To this end, they proposed that evacuation vehicles should be able to enter data on road conditions into the model, as well as the use of various sensor systems such as surveillance cameras or smartphone location tracking, to have up-to-date information on the distribution of the population. However, the usage of such live data also presents limitations, as the data volumes are immense and therefore require large amounts of storage capacity and computational power (Jotshi et al 2009).

This calculation of the optimal evacuation route, as performed by Jotshi et al. (2009) by using Dijkstra's algorithm, for example, is called an optimisation-based model. Naghdi et al. (2008) argue that finding the best optimisation-based path model is a major challenge and that there is

no such thing as the one best solution. All evacuation models present advantages and disadvantages. An optimal path is therefore highly dependent on what is defined as optimal and which factors are considered to be important (Naghdi et al. 2008). Evacuation optimisation models have two main objectives: (1) minimising total evacuation time and (2) maximising evacuation safety (Xiongfei et al. 2010). These two objectives can often conflict with each other, as, for example, short, time-efficient routes may not be safe. Thus, the challenge with evacuation tools is to find a balance between evacuation-time and safety (Xiongfei et al. 2010).

Another approach to generating evacuation maps for rescue workers has been developed by Ling et al. (2009), which uses the same optimisation model of Dijkstra's shortest path as Jotshi et al. (2008). They developed a tool which provides rescue workers and affected people with the optimal route to the next evacuation shelter for evacuation by vehicle. In addition to the factors proposed by Jotshi et al. (2008), they also take shelter capacity into account (Ling et al. 2009). They do this by assigning all people in the affected area to a specific shelter to ensure that no shelters become overcrowded. However, they point out that assigning people to shelters in order to maximise their capacity requires a great deal of computational power, which is why the tool only works in very small neighbourhoods (Ling et al. 2009). They also emphasise that when such evacuation tools are used in real evacuation situations, it is possible that mobile networks or the internet could collapse, meaning that these tools must be prepared for such eventualities. Moreover, the high number of users could also cause the tools to crash (Ling et al. 2009).

Overall, dynamic evacuation mapping indicates two main research limitations at this stage: computational constraints and the lack of models for immediate evacuation on foot. This highlights the need for a shift in evacuation modelling from rescue-worker-centred approaches towards tools supporting affected individuals, which is addressed in the following section.

2.3 Earthquake Evacuation Navigation Tools for Affected Individuals

As demonstrated in the research on evacuation behaviour, a leadership gap arises in the first few hours after an earthquake (NAZ 2004). During this time, a tool that assists evacuees themselves rather than rescuers in the evacuation would be of great assistance. Thus, in this thesis, these navigation tools are understood as *Earthquake Evacuation Navigation Tools (EENTs)*. EENTs differ from evacuation tools for rescue workers in two major ways. Firstly, direct evacuation after an earthquake takes place on foot and not by vehicle, as motorised traffic would be extremely dangerous in such a disorganised environment for both drivers and pedestrians (SED

2025b). EENTs are therefore designed for pedestrian evacuations. Secondly, immediately after an earthquake, people exhibit various social or psychological behaviour patterns that play a significant role in how and where they choose to evacuate (Ahmadi et al. 2025, Eiser et al. 2012). These elements should also be considered when designing an evacuation tool. However, many elements from previous evacuation mapping research may also be adopted. For evacuation on foot, the network model introduced by Southworth (1991) is applicable, and Cova's (1999) evacuation vulnerability model may likewise be applied to this road network. Moreover, as Jotshi et al. (2009) describe, evacuation routes may be defined through optimisation models that incorporate various factors such as debris from destroyed infrastructure or population density.

Ye et al. (2011) proposed one of the first models for evacuation on foot immediately after an earthquake. They created an optimisation model which calculates both the shortest as well as the fastest route to an evacuation site. Like Ling et al. (2009), they took the capacity of the evacuation sites into account, choosing green areas such as parks or fields. In addition, they considered the distribution of evacuees in the streets by adding more or less evacuation time in streets based on the people density. They did not, however, account for environmental factors of the earthquake, such as collapsing buildings (Ye et al. 2011). When comparing their model to real evacuation data they found that, following an earthquake, evacuees mostly do not go to the evacuation site they calculated, but to the one that evacuees are most familiar with (Ye et al. 2011). Shimura & Yamamoto (2014) published one of the key models for evacuation on foot after an earthquake. They created a navigation model for the case area of Tokyo, Japan, that determines the optimal evacuation routes based on Pareto ranking. In doing so, they included the following factors:

- Debris of Collapsed Buildings: Buildings may collapse based on the year of construction, the building type and the building material. When buildings collapse, the debris radius is calculated based on the height and ground area of the building. Based on this, the blockage of roads can be calculated.
- Road Width: The wider a road is, the more people can pass through it, allowing for a faster evacuation.
- Fire Hazard: Wooden buildings are likely to catch fire. Thus, evacuation routes near such buildings will be avoided.
- Population Density: Roads located in densely populated areas have longer evacuation times as it takes longer to get through large crowds of people.

- Distance: Longer evacuation routes result in higher evacuation time.

Using these factors, Shimura & Yamamoto (2014) calculated the best evacuation route using a Pareto ranking method as an optimisation model. The aim of the algorithm is to achieve a balance between evacuation time and the safety of the evacuation routes. This works by comparing numerous evacuation routes and selecting the route that is most balanced across all factors, with the goal of avoiding favouring any specific factor. Shimura & Yamamoto (2014) acknowledge several limitations of their model. First, the model is based solely on the nighttime population density distribution, not including other population distribution patterns. Second, the model assumes an earthquake scenario of undefined strength, limiting the usage in real scenarios. Third, due to the usage of the Pareto-based optimisation approach, the model lacks transparency to indicate why certain routes are selected. And finally, the model was neither evaluated by conducting an experiment or survey with participants nor does it incorporate human evacuation behaviour.

Another important paper in EENT research was published by Tsionas et al. (2016). They developed an evacuation vulnerability map which not only visualises the evacuation time per edge in a road network using similar factors to Shimura & Yamamoto (2014) but also includes anticipated traffic on roads and slope. They argue that the anticipated traffic indicates how many vehicles will be on the roads at the time of the earthquake, which limits the area of the roads and therefore leads to longer evacuation times as there is less space. Regarding the slope, they suggest that roads with steep slopes, regardless of their orientation, lead to longer evacuation times (Tsionas et al. 2016). However, some factors were not considered, for example fire hazard and population density. In addition, they only created a vulnerability map but did not include a model to determine the best evacuation route (Tsionas et al. 2016). Other prominent authors in the research field of EENT are Chen & Cheng (2020) and Ghafoori et al. (2022). Following an earthquake in Xi'an, China, Cheng & Cheng (2020) created a model that calculated the best evacuation routes and sites based on the effects of the earthquake. In this process, they noted that secondary environmental effects such as floodings or geological hazards, as well as infrastructural failures, such as blackouts or explosions at petrol stations, must also be taken into account. They also observed that evacuations pose an even greater challenge for people with limited mobility, such as elderly people, parents with strollers, or people with impairments, as earthquakes severely restrict the accessibility of roads. They therefore argue that secondary impacts and accessibility data should also be included in an evacuation model (Chen & Cheng 2020). Additionally, they evaluated their model by comparing it with how people actually

reacted after the earthquake. Chen & Cheng (2020) found that 61% of the population went to the evacuation sites they had calculated for them, while the rest either stayed at home, went to friends' or relatives' houses or went to other evacuation sites. They also found that the evacuation route taken was approximately 2.22 times longer on average than the one they had calculated. Finally, they found that younger and more educated people were more likely to choose the evacuation site that they had calculated for them. Chen & Cheng (2020) thus emphasise that evacuation tools represent a great potential for affected people and that further research into this area is needed. They also argue that the motivation behind people's choice of evacuation routes and destinations in connection with evacuation tools needs to be investigated further (Chen & Cheng 2020). Ghafoori et al. (2022) additionally state that EENTs would significantly facilitate the evacuation process for affected individuals and that the inclusion of real-time data from sensors or GPS on smartphones should also be incorporated into future research to obtain improved results. Furthermore, they proposed that EENTs should be tailored for individuals with special needs, such as those with impairments or other medical requirements (Ghafoori et al. 2022). All in all, although research on EENTs has made significant advances and progress in recent years, it still offers considerable potential for further investigation and development.

2.4 Positioning of the Thesis

The state of the art demonstrates that although extensive research has been conducted into earthquake evacuation behaviour and evacuation modelling, a clear gap between theoretical, technical implementation of evacuation models and practical, useable tools for affected people exists. Current approaches predominantly focus on optimisation-based evacuation models developed for rescue workers operating hours to days after an earthquake with the usage of vehicles. Although some research has been conducted into foot-based models for evacuations immediately after an earthquake, no approaches for adequate tools have yet been developed.

This thesis positions itself in this gap, proposing a proof of concept for such a navigation tool that aims to guide affected people to an evacuation site after an earthquake. In contrast to existing models, the proposed tool is user-oriented, allowing users to adjust parameters themselves and thus modify routes dynamically. Key parameters including earthquake magnitude, time of day, starting point and various possible destinations can be defined by the user, thereby bridging the gap between theoretical models and practical tools. Moreover, the tool integrates extended environmental and contextual factors that have not yet been addressed in EENTs, such as the spatial amplification of earthquake waves due to soil properties, secondary environmental disasters such as floodings and time-dependent shifts in population and traffic densities.

Finally, beyond the technical implementation, this thesis contributes empirical research into how such EENTs are perceived by the population and whether they can support individuals in their decision-making process. While various research has highlighted that human evacuation behaviour depends on a range of demographic, psychological, social and environmental factors, existing evacuation models rarely include these aspects. By evaluating the proposed tool in a user survey, this thesis examines the perceived helpfulness and functionality of the tool, hence providing insights into these cognitive aspects of the human decision-making process. In doing so, it examines the largely neglected intersection of human evacuation behaviour research and current evacuation modelling approaches. Overall, this thesis provides methodological, technical as well as empirical findings to the research of human-based earthquake evacuation tools.

3 Methods

The methods of this thesis consist of two parts, the development of the EENT and a survey to evaluate the created tool.

3.1 Development of the Navigation Tool

This chapter presents the methodology used to develop the EENT. First, the computational model and influencing factors are defined, followed by the description and reprocessing of the required data. Then the implementation of the EENT is presented by first explaining the computation of the environmental and contextual factors in the street network and secondly describing the application of a shortest path algorithm. Finally, it is demonstrated how the finished EENT can be used.

3.1.1 Computational Model and Influencing Factors

The EENT is based upon established concepts of evacuation modelling, including the network model of Southworth (1991), the vulnerability mapping framework introduced by Cova (1991) and various optimisation-based evacuation model approaches (Ye et al. 2011, Shimura & Yamamoto 2014, Tsionas et al. 2016).

The EENT is fundamentally structured around the spatial road network of the city of Zurich, which is represented as a weighted graph. Intersections are modelled as nodes and road sections between nodes are modelled as edges. Each edge is defined as a walkable road section that can be used in a potential evacuation route. By using a network-based model, attributes can be stored on these edges. As a baseline, the *walking time* is stored as an attribute which indicates how long it takes to walk through this edge in a non-earthquake scenario without the disruption of any environmental factors. Based on the vulnerability mapping approach of Cova (1991), this baseline walking time is influenced by contextual and hazard dependent factors in the event of an earthquake. These factors may modify the walking time in two ways, by either increasing the time required to traverse the edge, or rendering edges blocked and completely impassable. This framework thus allows the spatial effects of an earthquake to be stored in the form of varying walking time changes in a road network.

The influence of these factors is computed individually and then spatially layered over the street network, modifying the walking time. This iterative process is done until all factors are layered on top of each other and a final walking time is obtained. The computed value represents the time it takes to traverse the edge under the earthquake and is stored as the *evacuation time*

attribute per edge. This calculation is performed using a multi-criteria evaluation (MCE). An MCE is a method used in GIS to support decision-making based on multiple criteria (Eastmann 1999). It is used to combine influencing factors of an object into a map and then determine the spatial distribution of said object. This is done by adding up or multiplying all factors into one aggregated measure (Eastmann 1999). In this context, the evaluated object is the evacuation time in an earthquake scenario, and the criteria are the hazard and contextual factors. An MCE is a particularly suitable method in this case as it allows the influence of various factors to be examined and the computation process to be defined flexibly. In addition, it offers a high degree of transparency as the contribution of each factor can be traced. A visual representation of the evacuation time calculation in the form of an MCE can be seen in Figure 4.

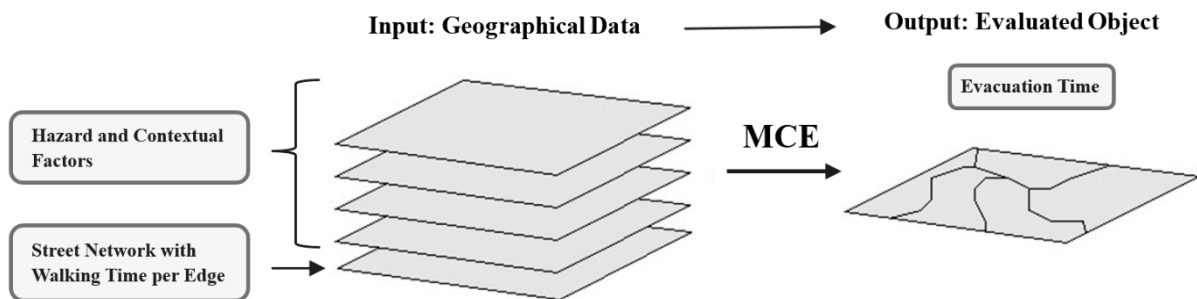


Figure 4: Multi-criteria evaluation approach to calculate the evacuation time per edge in a street network (Alkema et al. 2014)

Although MCE frameworks often include the assigning of weights to the individual criteria whereby factors can have a greater or lesser influence on the result, this was not done in this EENT calculation. Instead, based on existing approaches, it is assumed that all criteria have equal significance (Shimura & Yamamoto 2014).

The influencing factors used to determine the evacuation time were selected based on the relevant literature as well as their data availability. The following factors are incorporated into the model:

- Road Width: The width of a road indicates its capacity for pedestrian traffic and is also used to calculate the potential impact of debris, leading to partially or completely blocked streets (Shimura & Yamamoto 2014).
- Road Type: Some types of roads react in distinct ways to earthquakes. Bridges tend to collapse while tunnels are considered safe in Switzerland (NAZ 2004).
- Debris: Debris from collapsed buildings can partially or completely block roads. The year of construction of a building and the number of floors can be used to make an assumption

about how vulnerable the building is to earthquakes. The height of the building and floor plan area is used to calculate the debris area in the event of collapse (SED 2025c, Shimura & Yamamoto 2014).

- Population Density: The population density indicates the spatial distribution of evacuees. Higher densities result in slower evacuations as there is less space available (Glickman 1987, Southworth 1991).
- Traffic Density: The traffic density indicates the spatial distribution of vehicles on the roads. Since vehicles should be vacated after an earthquake, high traffic density results in a large number of abandoned vehicles obstructing a road and consequently less space, which leads to a slower evacuation (Tsionas et al. 2016).
- Slope: Steep roads increase evacuation time (Tsionas et al. 2016).
- Water Bodies: Water bodies can cause floods as a secondary effect of an earthquake, thereby blocking or restricting possible evacuation routes (Chen & Cheng 2020).
- Soil Amplification: Seismic waves can be spatially amplified or attenuated by soil properties. Soil amplification is analysed for three earthquake scenarios with magnitudes of 5.5, 5.75 and 6 (Bergamo et al. 2023).

The population and traffic density factors are available in two temporal forms: daytime and nighttime density. As argued by Glickman (1987), it is essential to include the spatial distribution of people depending on the time of day when modelling evacuation routes. Accordingly, population density is represented by residential density (nighttime) and workplace density (daytime), while traffic density is differentiated by time of day using corresponding datasets.

All contributing factors influence evacuation time, mainly by restricting or completely blocking the area of road sections, amplifying or attenuating other effects of the earthquake, or facilitating or hindering the movement on routes. Furthermore, data on green areas, which are considered earthquake evacuation sites in Switzerland, as well as hospitals as alternative locations, are used (NAZ 2004). The spatial outline of the city of Zurich is used to spatially scale the factors if they are geographically too large. Some factors discussed in the literature are not considered in this tool due to limited or unavailable data. These include road accessibility (such as stairs or road surface type), fire hazard probability of infrastructure, and landslide vulnerability. The absence of these factors is further discussed in the limitations section.

Finally, the optimal evacuation route is calculated based on the optimisation model of Dijkstra's shortest path algorithm (Dijkstra 1959). Users can enter their starting point and destination, choosing from evacuation sites, hospitals or custom points. The algorithm then calculates and

visualizes both the best route and the best destination (if no custom point has been selected). The optimal route is defined as the route that reaches the fastest accessible destination in the shortest time possible, based on the evacuation times calculated in the MCE. Since the impacts of an earthquake are incorporated in the MCE, the model is a combination of prioritising safe routes and fast routes. As an example, routes that would be the fastest in a non-earthquake scenario may be assigned a high evacuation time due to the effects of an earthquake and would therefore be avoided. The tool would then choose the evacuation route with the lowest evacuation time. Thus, instead of minimising distance, the algorithm minimises the total evacuation time, defined as the sum of the evacuation times of all edges along a route.

In the final EENT users can adjust the parameters of earthquake magnitude and time of the day, thereby modifying the factors used in the MCE and potentially generating different evacuation routes based on the scenario. An overview of the methodology to develop the EENT can be seen in the workflow diagram in Figure 5.

Methodological Workflow of the EENT

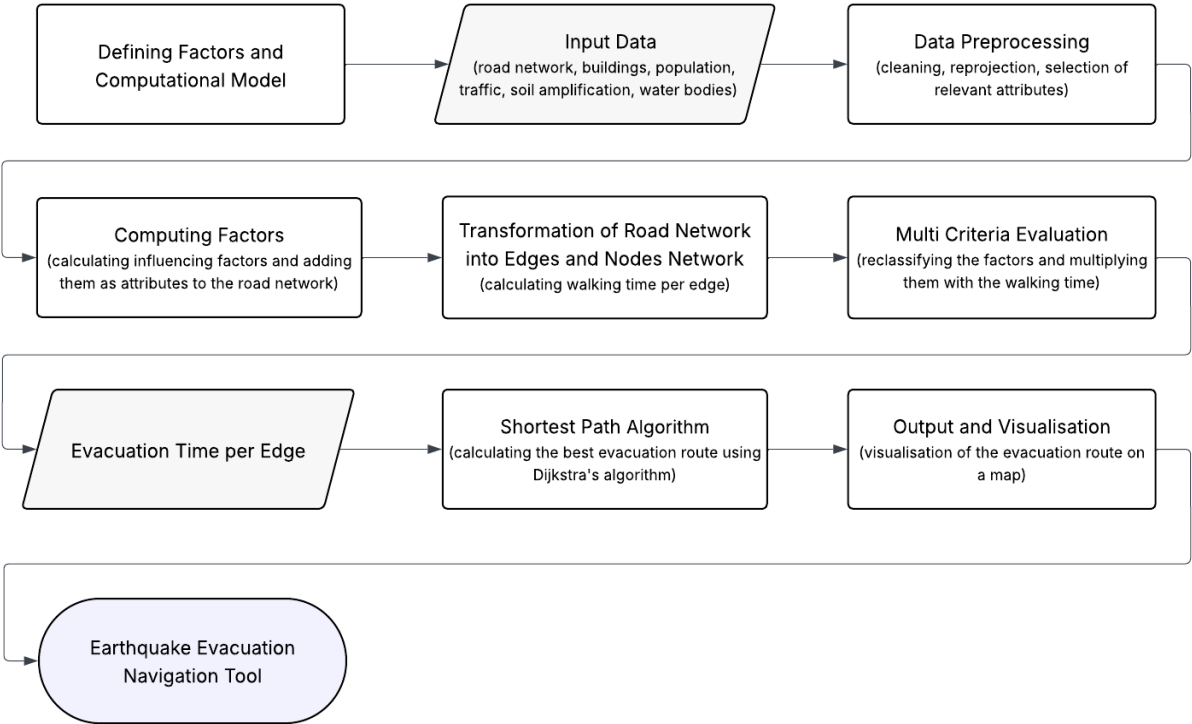


Figure 5: Methodological workflow for the development of the EENT

3.1.2 Data and Reprocessing

All datasets, except the soil amplification data, used for developing the EENT are publicly available and licenced under a Creative Commons CC Zero License. The soil amplification dataset is available under a CCBY-Licence. All datasets were reprocessed using the open-source GIS program QGIS.

The entire road network, including information on the length, width and type of road (bridge, tunnel) and the bodies of water were obtained from Swisstopo's TLM model (Swisstopo 2022). The TLM model (Topographic Landscape Model) contains all landscape-defining elements throughout Switzerland in a vector format. It has a high spatial resolution ranging from one decimetre for streets to three metres for water bodies (Swisstopo 2022). The age, number of floors and floor plan area of buildings are provided by the Swiss Federal Statistical Office (2025) in the building and residential area register. This is a point dataset where each point represents a building. The hospital dataset was provided from GeoZ (Department of Geomatics and Surveying) (2024) of the city of Zurich, where hospitals are stored as points.

The residential population as well as the workplace density data was obtained from the Swiss Federal Statistical Office. The datasets on population and households (Swiss Federal Statistical Office 2024) and statistics on business structure (Swiss Federal Statistical Office 2022) were used for this purpose. Both are available in a raster format with a spatial resolution of 100 x 100 metres, with the number of people living or working in each grid point stored.

The height of the buildings was calculated from two datasets: the DHM25 (swisstopo 2024a) and the swissSURFACE3D (swisstopo 2024b) model. The DHM25 is a digital terrain model (DTM) that contains the height of the Swiss-wide topography without man-made objects. It is a raster record with a spatial resolution of 25 x 25 metres. The swissSurface3D model is a digital surface model (DSM) that depicts the shape of the earth's surface throughout Switzerland with man-made objects. It is a raster dataset with a spatial resolution of 0.5 x 0.5 metres. The spatial resolution of the DSM was reduced to 25 x 25 metres in QGIS as the high resolution of 0.5 x 0.5 metres required too long to be loaded and it had to be at the same resolution as the DTM, to calculate the height of the buildings. The height of the buildings was then calculated by subtracting the DTM from the DSM in the raster calculator in QGIS. This resulted in a raster dataset representing the mean height of infrastructure per 25 × 25 m pixel. Moreover, the slope was calculated from the swisstopo DHM25 (2024a) dataset by using the function `r.slope.aspect` in QGIS.

The traffic density was defined by the proxy of the traffic noise level. The assumption was made that high road noise corresponds to high road volume. This proxy was chosen as direct data on traffic volume was not available. The data was obtained from the traffic noise dataset of the UGZ (Department of Health and Environment) (2024) of the city of Zurich. This is a vector dataset in which roads are represented as lines with their road noise emissions during the day or night.

Green spaces as evacuation sites were identified by the City of Zurich's biotope type mapping (2021). Only parks, cemeteries, botanical gardens, fields and artificial meadows were selected from the dataset. In addition, only areas of more than 0.5 hectares were selected as evacuation sites must have sufficient open space to be suitable for evacuation (NAZ 2004).

The soil amplification was provided by the dataset of Bergamo et al. (2023). It spatially indicates the extent to which seismic waves are amplified or attenuated by the soil based on topographic and geological information. The value 1 indicates no amplification or attenuation of the waves. Values below 1 indicate an attenuation and values above 1 indicate an amplification of the waves. The data consists of three datasets representing different earthquake intensities. In each scenarios a theoretical earthquake hits the city of Zurich with intensities of 8, 8.5 and 9, respectively. Intensity is a unit to describe the force of an earthquake, with intensity 8 approximately corresponding to an earthquake of magnitude 5.5, intensity 8.5 to an earthquake of magnitude 5.75, and intensity 9 to an earthquake of magnitude 6 (SED 2025d).

Finally, all used datasets had to be geographically cut to the city of Zurich, if they weren't already in that spatial extend. The geographical outline of the city of Zurich was created by selecting the city of Zurich from the municipal boundaries (OGD dataset) (Open Data Zurich 2023).

3.1.3 Factor Computation

The calculation of the factors, as well as the entire EENT, was performed in Python 3. These computations were based on Zurich's road network. All factors were derived in a way so they could be added as attributes to the individual roads in the network, which are represented as geographical lines. The spatial road network can be seen in Figure 6.

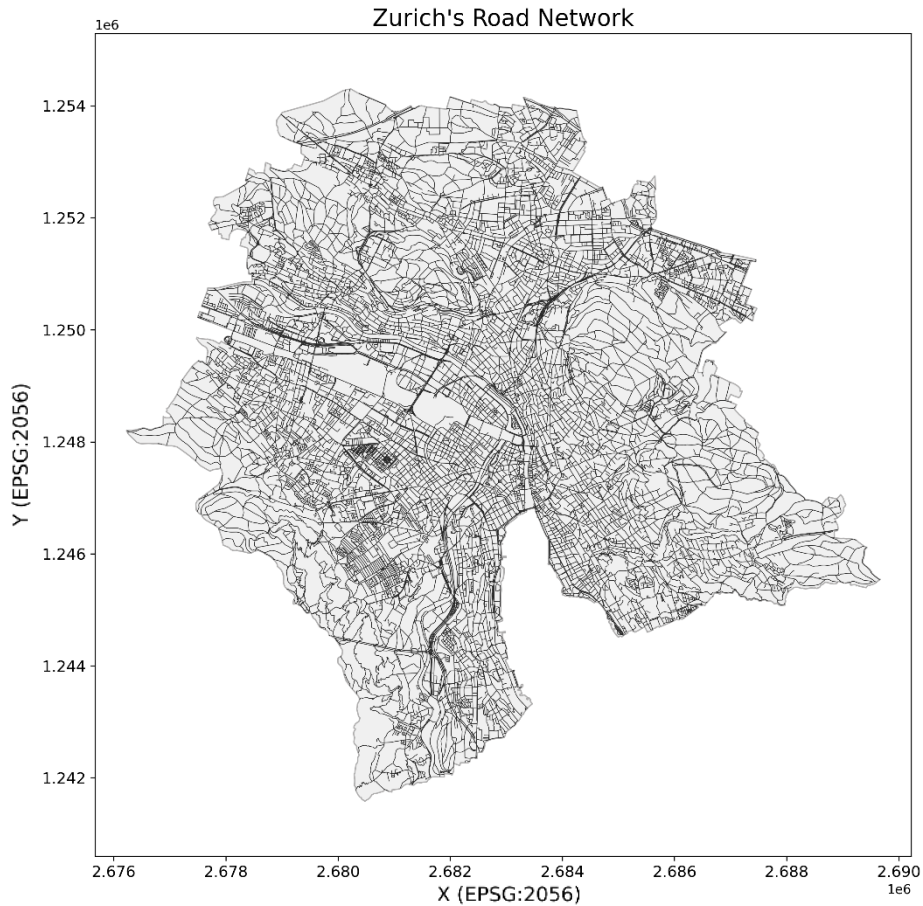


Figure 6: Map of Zurich's road network used as a basis in the EENT

First, all datasets were converted to the EPSG 2056 coordinate system, which is used for projection in Switzerland. Subsequently, all criteria were appended as attributes to the lines in the road network. For raster-based criteria, namely slope, residential density and workplace density, this was performed by calculating the mean value of all raster cells intersecting a street and then assigning this value as the corresponding street attribute. The width of the roads was stored in the road network dataset as a road type string attribute and had to be converted to numerical values. To do this, the strings were assigned their corresponding numerical width value in a dictionary, whereby assumptions had to be made about the width of certain object types. Most road objects had their exact width included in their road type attribute, for example, “10 Meter Strasse” (10 meter street). However, some road objects did not have defined widths, such as the road types “Platz” (square), “Zufahrt” (driveway), “Autobahn” (motorway) and others. For these road objects, widths were defined based on the road standards of the TAZ (civil engineering office) of the city of Zurich (2025). The road traffic data was added as an attribute in the road network by taking the traffic value with the highest spatial overlap for each road. Not all roads had road traffic data, in which case NA values were added for this attribute. Road types such as tunnels or bridges were already included as attributes in the street network dataset.

To calculate the collapse vulnerability of buildings, each building in Zurich was first assigned its calculated height. This height was derived from a raster dataset and had to be mapped to a point dataset, where each point represents a building. However, as the calculated building height represents the average height per 25 x 25 metre pixel, the resulting values are not entirely accurate. The heights of the buildings are systematically underestimated, as areas without infrastructure, such as surrounding ground areas, were included in the mean calculated pixel value as well. To compensate for this, all building heights were adjusted upwards by using the minimum and maximum offsets derived from comparison with ground truth data. In the next step, the soil amplification data was added as an attribute to the corresponding building in the point dataset. In addition, the floor plan area of the building was added as a geometry attribute, whereby the geometric footprint was simplified as a circle. Based on a classification scheme from the Swiss Seismological Service (SED 2025c), all buildings in the dataset were then assigned to a building type based on the year of construction and the number of floors. Based on the same classification (SED 2025c), these building types were then assigned a probability of how severely they would be damaged in earthquakes of different strengths. All buildings were thus assigned a damage grade for earthquakes with an intensity of 8 (magnitude 5.5), 8.5 (magnitude 5.75) and 9 (magnitude 6), which displayed the highest probability. The earthquake scenarios are based on the soil amplification data, which indicates how strongly the ground would shake in the corresponding scenario. The assigned damage grades range from 1 to 5 and are defined as follows (Conseil de l'Europe 1998):

- Damage Grade 1: There is negligible to slight damage inside buildings.
- Damage Grade 2: There is damage inside buildings. No buildings collapse.
- Damage Grade 3: There is severe damage inside buildings. Most buildings do not collapse.
- Damage Grade 4: Buildings collapse partially to completely.
- Damage Grade 5: Buildings collapse completely.

The computed damage grades of the buildings in the three earthquake scenarios are visualised in Figures 7 to 9.

Zurich's Buildings by Damage Grade for Earthquake Intensity 8

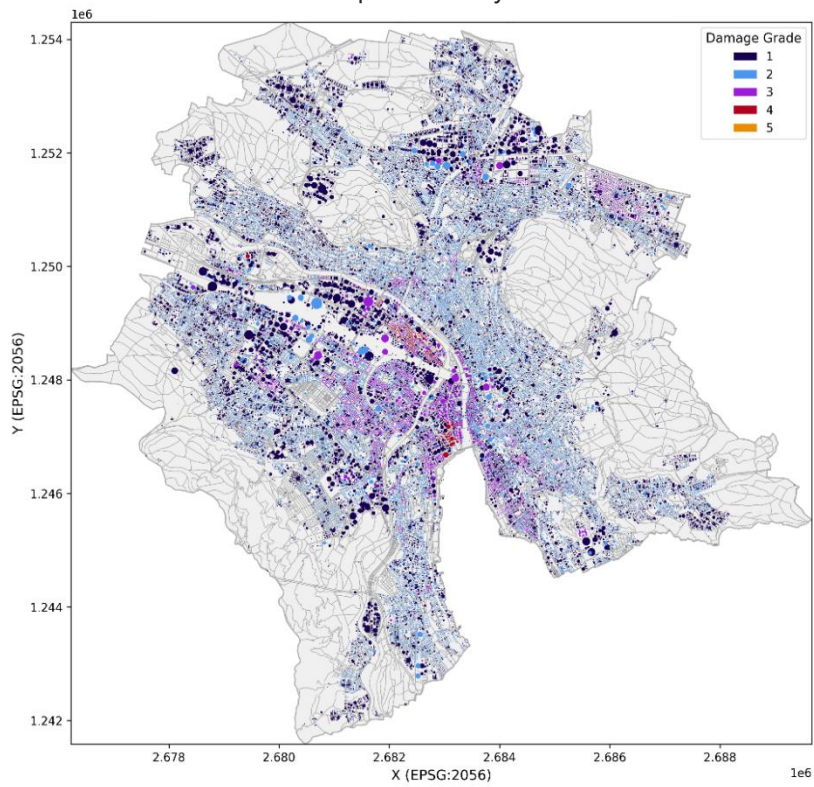


Figure 7: Map of all simplified building footprints in Zurich coloured according to their damage grade for an earthquake of intensity 8 (magnitude 5.5)

Zurich's Buildings by Damage Grade for Earthquake Intensity 8.5

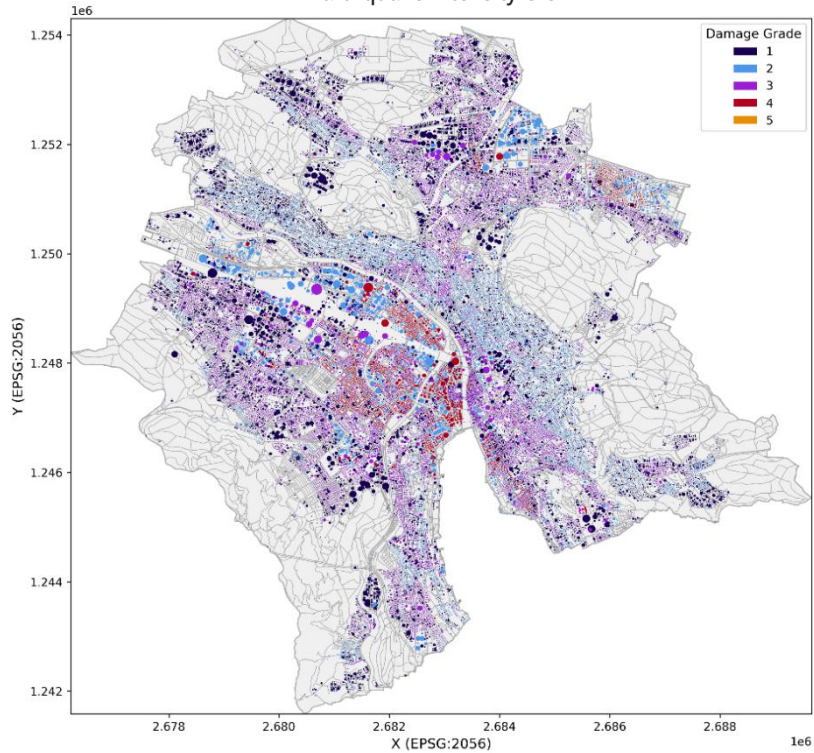


Figure 8: Map of all simplified building footprints in Zurich coloured according to their damage grade for an earthquake of intensity 8.5 (magnitude 5.75)

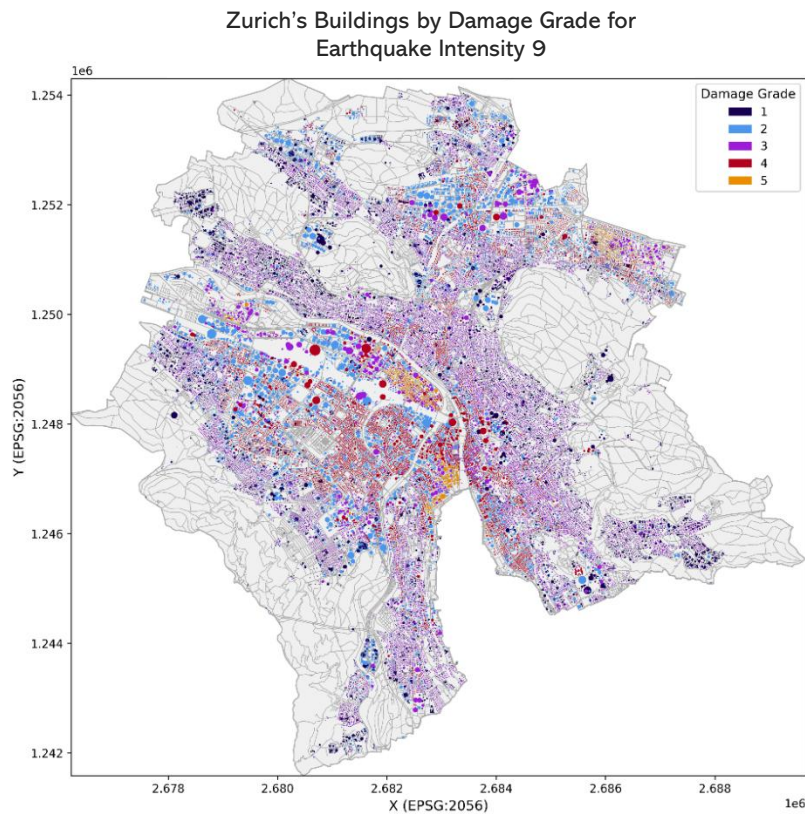


Figure 9: Map of all simplified building footprints in Zurich coloured according to their damage grade for an earthquake of intensity 9 (magnitude 6)

Given the collapse damage grades of buildings, the debris area in case of collapse could be estimated for the three earthquake scenarios. Based on Santarelli et al. (2018), the debris of fully collapsed buildings is approximately 30% of the structure's original height, meaning that 70% of height is lost. It is assumed that buildings with a damage grade of 5 are completely destroyed and thus reduced by 70% of their height. Buildings with a damage grade of 4 are assumed to be half as severely damaged as those with a damage grade of 5 and are therefore reduced in size by 35% of their original height. Buildings with a damage grade of 3 or lower are assumed not to collapse and therefore do not form a debris area. Based on the original and post-collapse building heights and the floor plan area, the debris radius was calculated by using the building volume. This debris area was added as a new geometry attribute as a footprint to the building points. If a building does not collapse, it retained its original footprint. The debris areas for the three earthquakes are illustrated in Figures 10 to 12.

Debris Footprint of Collapsed Buildings for Earthquake Intensity 8

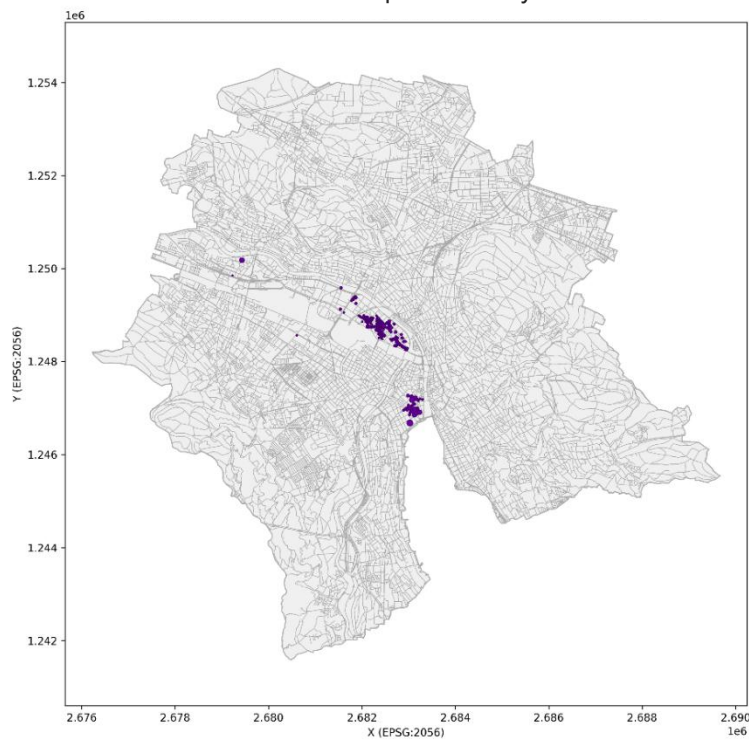


Figure 10: Map of all debris footprints in Zurich for an earthquake of intensity 8 (magnitude 5.5). Buildings with damage grade 4 collapse partially and damage grade 5 completely.

Debris Footprint of Collapsed Buildings for Earthquake Intensity 8.5

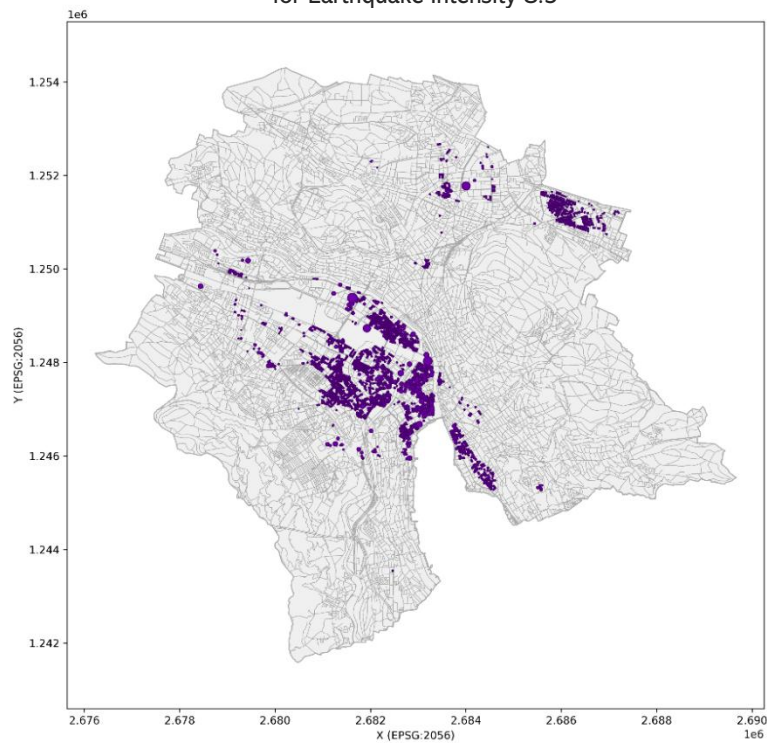


Figure 11: Map of all debris footprints in Zurich for an earthquake of intensity 8.5 (magnitude 5.75). Buildings with damage grade 4 collapse partially and damage grade 5 completely.

Debris Footprint of Collapsed Buildings for Earthquake Intensity 9

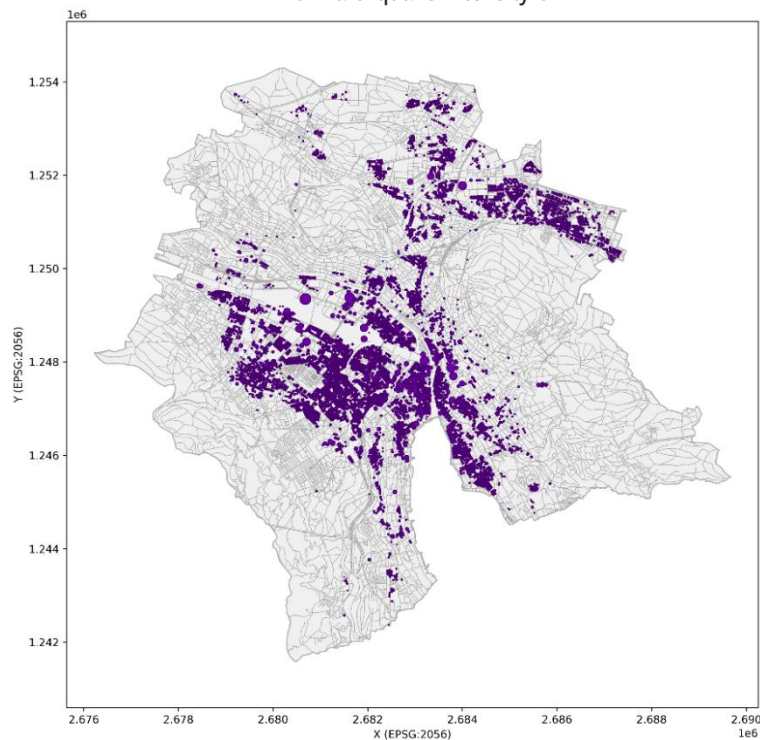


Figure 12: Map of all debris footprints in Zurich for an earthquake of intensity 9 (magnitude 6). Buildings with damage grade 4 collapse partially and damage grade 5 completely.

Finally, the debris area of collapsed buildings was used to calculate partially and fully blocked streets. Road segments, which were originally represented as line geometries, were buffered using their width attribute and thus converted into area geometries. The debris layer was then subtracted spatially from the buffered street layer to calculate the percentage of each street that had been subtracted and thereby covered by debris. This value was added to each street as an attribute for its blocked street percentage. In addition, for each road, it was assessed whether it was completely separated in one or more places by this subtraction. This was done by determining whether a road now consisted of several separated lines or still consisted as a whole. All streets were given an attribute named “fully_blocked”, which was set to “yes” for streets that had been separated at least in one place and to “no” for all other streets. These two attributes thus indicated the percentage of a street that was covered by debris and whether streets were completely blocked across their width, making them impassable. Furthermore, for roads that were bridges, it was assumed in all earthquake scenarios that they would collapse, and therefore their value was set to “yes” for “fully_blocked”. On the other hand, roads that were tunnels were assumed not to collapse or be affected by debris, which is why these roads were set to “no” for “fully_blocked” and the blocked street percentage was set to 0. This is a generalisation

and is derived from Switzerland's earthquake concept (NAZ 2004). The results of the street blockage can be seen for the three earthquake scenarios in Figures 13 to 15.

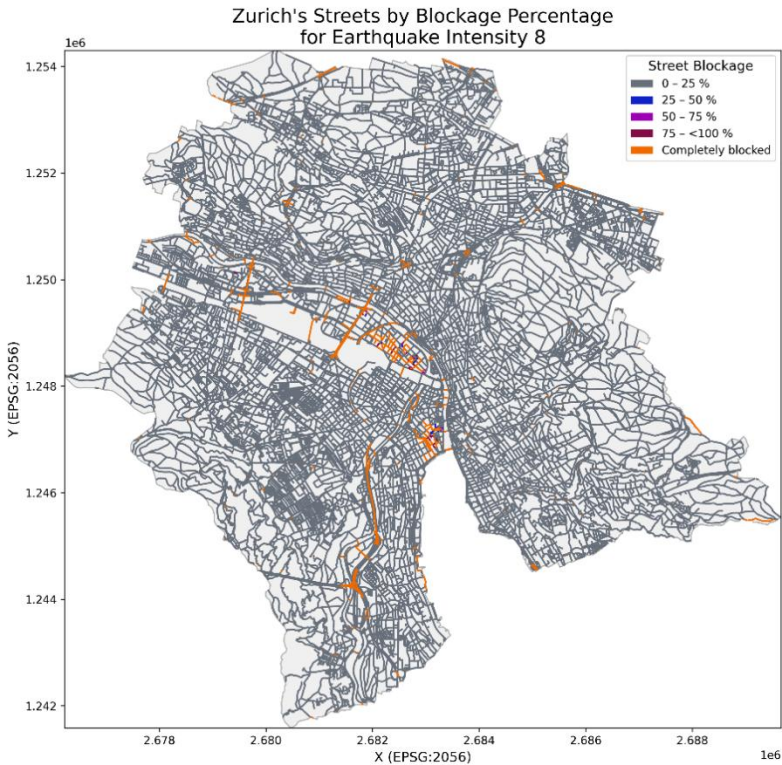


Figure 13: Map of the road blockage in Zurich for an earthquake of intensity 8 (magnitude 5.5)

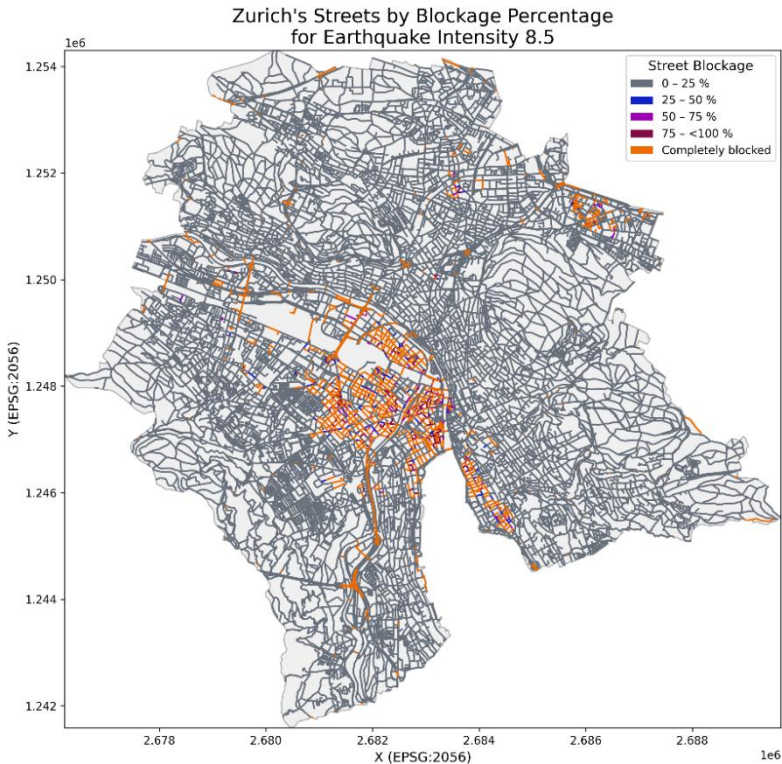


Figure 14: Map of the road blockage in Zurich for an earthquake of intensity 8.5 (magnitude 5.75)

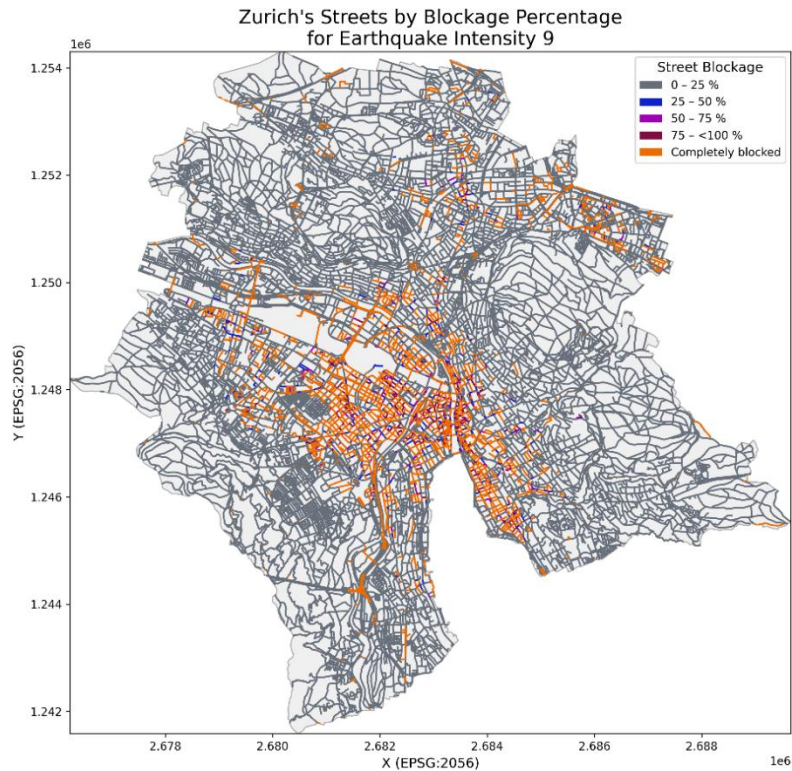


Figure 15: Map of the road blockage in Zurich for an earthquake of intensity 9 (magnitude 6)

Regarding the last criterion of flooding of bodies of water, based on Strupler et al. (2018), no considerable flooding of lakes or rivers is expected for earthquakes with a magnitude of 5.5 to 6 in Zurich. Therefore, the secondary effects of flooding were disregarded in this case. However, although no flooding is expected in the example of Zurich, floodings should be included when applying the tool to other locations.

3.1.4 Multi-Criteria Evaluation

In the next step, the processed criteria were aggregated to obtain the evacuation time using an MCE. To do this, the road network was converted into a weighted graph with edges and nodes. The walking time per edge was added as a base attribute. This was calculated based on the distance and walking speed, which depends on crowd density. The higher the crowd density, the lower the walking speed (Beermann & Sieben 2023). The mean walking speed without the influence of crowds is 1.24 metres per second (Seyfried et al. 2005). Using the criteria of daytime and nighttime crowd densities, which are represented by residential and workplace density, the walking speeds were assigned based on Seyfried et al. (2005) as defined in Table 1.

Table 1: Walking speed in different crowd densities
(Seyfried et al. 2005)

Crowd density [people / m ²]	Walking Speed [m/s]
0 – 0.7	1.24
>0.7 – 1.1	0.9
>1.1 – 1.5	0.45
>1.5 – 2	0.23
>2	0.17

For each edge, the walking speeds were then multiplied by the length of the edge, resulting in the baseline walking times. Due to the temporal division into daytime and nighttime distribution of the population, this also resulted in two datasets for day and night.

For the two missing criteria of traffic density and road blockage due to debris, their impact was then calculated on top of the walking time. This was done by multiplying each criteria layer with the walking time layer. For this, the criteria values were reclassified as follows: Value 1 indicates no influence on walking time, and all values above 1 increase walking time. If edges are impassable due to completely blocked streets, meaning the attribute “fully_blocked” was set to “yes”, walking time was increased to infinity, causing these edges never to be selected when calculating an evacuation route. The criteria were divided into 5 equal intervals, with the interval with the smallest impact, e.g. the least traffic or debris on roads, being assigned a value of 1.1. The other intervals were then assigned values of 1.2, 1.3, 1.4 and 1.5 in ascending order. This linear reclassification was based on Shimura & Yamamoto (2014) and Tsionas et al. (2016). Edges that are not affected by a criterion were assigned a value of 1 for the respective criterion. Since there were three earthquake scenarios for road blockages and the walking time had been calculated for the day and night scenarios, the result was a dataset that indicates the evacuation time in the road network per edge for six scenarios; daytime magnitude 5.5, daytime magnitude 5.75, daytime magnitude 6, nighttime magnitude 5.5, nighttime magnitude 5.75 and nighttime magnitude 6. Figures 16 and 17 display the calculated evacuation time for a magnitude 6 earthquake during the day and at night.

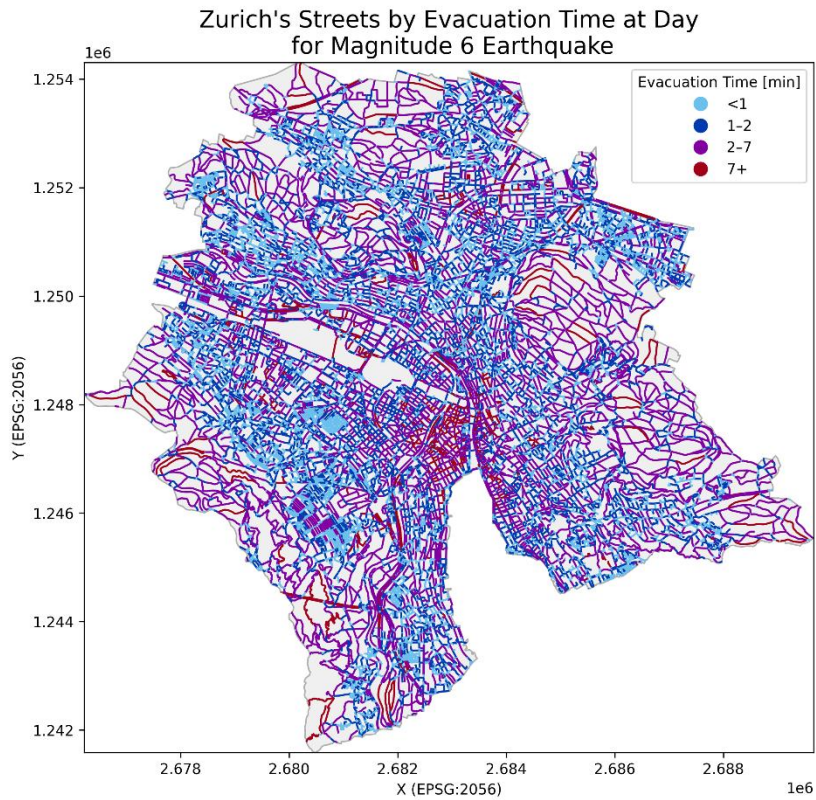


Figure 16: Map of evacuation time per edge in Zurich's street network for an earthquake of magnitude 6 during the day

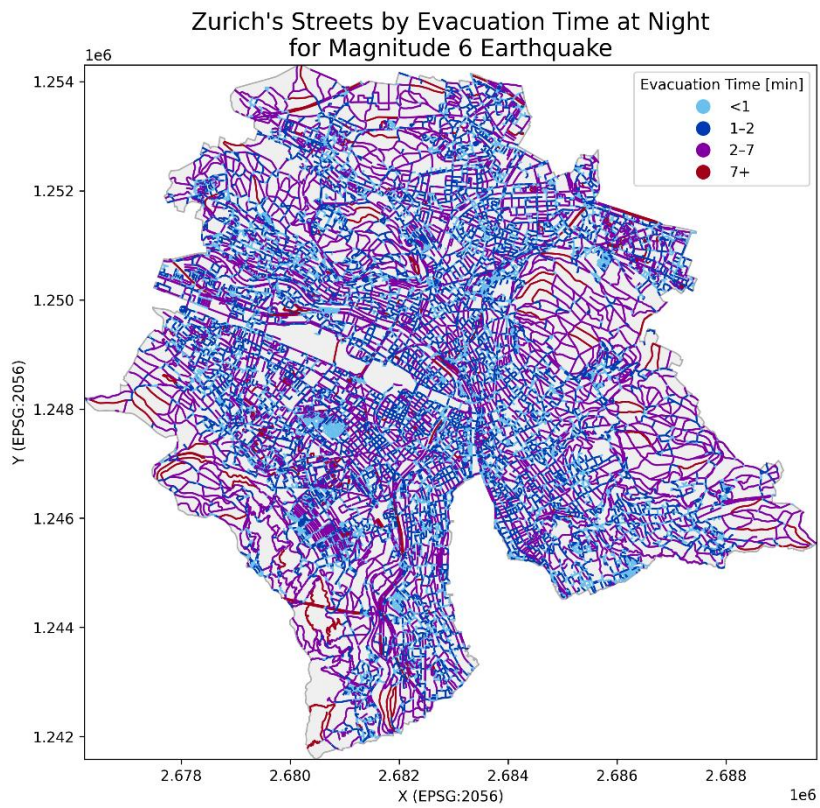


Figure 17: Map of evacuation time per edge in Zurich's street network for an earthquake of magnitude 6 during the night

3.1.5 Shortest Path Algorithm

Using the calculated evacuation times, the best evacuation routes could then be computed and visualised by using a shortest path algorithm. For this, Dijkstra's shortest path algorithm was applied (Dijkstra 1959). The algorithm works based on the starting location and the destination point (evacuation site, hospital or custom point), which must be entered into the code as variables from the user. For evacuation sites and hospitals, Dijkstra's algorithm computes the total evacuation time for all accessible destination nodes of all possible routes. The route with the shortest time to the corresponding destination is selected. For a custom point, the algorithm computes the evacuation times of all possible routes to the one destination point and selects the route with the shortest total evacuation time.

At this stage, the street's slope was intended to be incorporated into the calculation, which would increase the evacuation time when routes go upwards and decrease it when they go downwards. However, due to the directionality of the slope, meaning that an edge can have a longer or shorter evacuation time depending on the direction of travel, the algorithm would have to evaluate substantially more routes. This led to an excessively long calculation time for which there was insufficient computational power available. Consequently, the slope was not included in the final EENT. The same applied to the inclusion of evacuation site capacity. To ensure that the system would select an evacuation site that had sufficient capacity for the user, the algorithm would have to assign every individual in Zurich to an evacuation site so that the sites would be filled evenly. This would likewise require excessive computational power, which is why evacuation site capacity was not included in the final EENT.

3.1.6 Tool Implementation

The finalized tool was designed in such a way that users first selected their starting point on a map. They then had to specify the time of day, choosing between “day” and “night”, the strength of the earthquake, choosing between magnitudes 5.5, 5.75 and 6, and finally the destination type, choosing between “park” (which are emergency evacuation sites in Switzerland), “hospital” or “custom”. If “custom” was selected, they were also required to specify the coordinates of this point. Based on the user input, the evacuation route was then calculated and visualised on a map.

Since the focus of this model lay on the underlying computational process rather than the visual design of the final map, a simple design was used. As the base map, a colour map displaying

roads, buildings, green spaces and bodies of water was chosen. The names of important roads, parks and neighbourhoods were also displayed to help with orientation. The starting point was visualised as a white dot with a black border and the evacuation route as a black dotted line. Destinations were displayed as green polygons for evacuation sites, light blue pins for hospitals, and red pins for custom locations. These visual design choices were intended to support intuitive map interpretation, by selecting symbology which represented the type of destination. Evacuation sites were chosen as green polygons, reflecting the common cartographic representation of parks and green areas. Hospitals were chosen as light blue pins, as this colour is mostly associated with medical services in map design. Finally, custom points were chosen as red pins, consistent with conventions used in popular navigation apps, such as Google Maps. Examples of calculated evacuation routes can be found in the results section.

3.2 Survey

To assess whether the developed tool can support users in making better evacuation decisions after an earthquake, a survey was conducted, which acts as an online experiment. This section thus explains the survey design by first discussing the experimental design, then the survey structure and finally the execution of the survey. In addition, some analytical methods for evaluating the survey are introduced. The whole survey can be found in the appendix.

3.2.1 Experimental Design

Surveys are an essential scientific tool for obtaining a wide range of quantitative and qualitative information from individuals. This is often done using questionnaires, which serve as a method for obtaining standardised results, as all participants answer the same questions (Roopa & Rani 2012). The great benefit of surveys is that they allow complex factors such as perception, knowledge or confidence to be measured (Stantcheva 2022). There are various methods to conduct surveys. In the scope of this thesis an online survey was conducted. The advantage of online surveys is that they are easy to distribute, which allows more people to be reached. In addition, participants can respond more neutrally than they would in an in-person survey, as there is less chance of bias or distortion from the interviewer (Martin 2008). The online tool Limesurvey (<https://www.limesurvey.org>) was used to create the online survey. Limesurvey is open source and allows various question types to be integrated.

The aim of this survey is to address research question 3: *“How can earthquake evacuation navigation tools support users in evacuation decision-making?”*. In this context, the decision-making process refers to the process whereby a person must decide, after a strong earthquake,

which evacuation site to go to and which route to take. To this end, a survey was created that examined both the participants' decision-making before being introduced to the evacuation-tool as well as the perception of the tool after being introduced to it. This approach allows to capture how the decision-making-process in an earthquake evacuation situation works and by which factors it is influenced. In addition, the survey aims to assess the participants perceived helpfulness and functionality of the tool and whether they believe that such a tool could support them in an evacuation situation. Moreover, the survey aims to examine whether different population groups display different patterns in decision-making or the perception of the tool. Such identified relationships can be useful in the design and implementation for evacuation apps. As the survey focuses on personal judgement and behaviour, many questions are subjective and open-ended. This question design was chosen to gain a better understanding of participants' opinions and feelings.

Throughout the survey, the EENT was referred to as a navigation evacuation app to simplify the language. This was done as the terms "tool" or "code" are difficult to grasp if one is not familiar in this field. Apps, on the other hand, are used every day and are generally understood. Simplifying technical jargon is important when conducting surveys that should be accessible to the broad public (Arundel 2023). Moreover, the survey also aims to examine if such an evacuation app could potentially support users in taking decisions in earthquake evacuation situations, thereby indicating whether the concept shows potential to be developed into an app in future research.

There is no specific target group for the survey, as all people can be exposed to an earthquake and thus should be able to use the app. Although a part of the survey includes map elements that are located in the city of Zurich, it is not a requirement that participants reside in Zurich. Local knowledge may be used when answering the questions but is not required.

3.2.2 Survey Structure

The survey was designed to take approximately 10-15 minutes to complete and was structured into three main parts:

- Part 1: sociodemographic questions and questions about prior knowledge of earthquakes, the city of Zurich and the usage of (warning) apps
- Part 2: decision-making task, where participants had to choose an evacuation site in an earthquake scenario and argue why they chose it
- Part 3: introduction of the evacuation tool and questions about the participants' perception of the tool

The survey started with an introductory text, explaining its broad content and structure. In part one of the survey, participants had to first fill out various sociodemographic questions and rate their knowledge on earthquakes as well as their local knowledge of the city of Zurich. The knowledge questions were measured using 5-point Likert scales ranging from 1 (low knowledge) to 5 (high knowledge). As described by McLeod (2025), Likert scales are ideal for asking questions about knowledge, opinions or feelings and were thus used multiple times in this survey. In addition, two open questions were asked on how participants react during and after an earthquake. The last questions in part one of the survey concerned the smartphone usage of the participants. Three 5-point Likert scale questions were asked about how often participants use their smartphones, how often they download apps and how much they use apps with location tracking. These questions were asked to determine knowledge and trust in smartphones, as this can influence the participants' willingness of using such an evacuation app. Participants were also asked if they were using any evacuation apps and, if so, which ones. They could either choose from existing apps or list other apps.

In the second part of the survey participants had to complete a decision-making task. They were presented with three map sections of Zurich, each marked with a starting location and three safe evacuation sites in the vicinity of that location (see Figures 18 – 20). Participants were asked to imagine themselves in a situation where a strong earthquake of magnitude 6 had struck the city at 3 p.m. in the afternoon and they had to choose which evacuation site to evacuate to. For each map section scenario, participants had to:

- explain the reason behind their decision,
- state how confident they were in their choice

- and argue whether they would change their decision if it were 3 a.m. at night.

This task design was chosen to obtain responses that display authenticity and personal perspective. According to Arundel (2023), questions intended to inspire reflection and encourage personal behaviours are best posed by placing individuals in situations designed to be captivating and thought-provoking.

For this, the following three spatial scenarios were chosen: District 1, District 5 (Industriequartier) and Oerlikon. For all three scenarios the EENT also calculated the evacuation site that could be reached the fastest based on the computed evacuation time. In each of the three maps, one of the three evacuation sites was thus the one calculated by the EENT and the other two were the evacuation sites closest to the starting point apart from the one computed by the EENT. On each map, the starting point was marked in red, and the three possible evacuation destinations were marked in green, labelled A, B, and C so that participants could indicate their chosen destination by its letter. In addition, points of interest were added to the maps for orientation purposes, such as the names of neighbourhoods and important landmarks (like train stations or universities). Furthermore, the maps were in colour and showed the names of major roads, enabling users to orientate themselves as efficiently as possible and gain an understanding of the displayed environment.

Each of the three map scenarios was selected to highlight a key factor relevant for calculating evacuation routes. This was done by selecting locations that are strongly influenced by one specific key factor. Inevitably, all factors influence the final selection of the evacuation tool, but in the selected scenarios, one factor is always the most crucial decisive element. In addition, it was ensured that the spatially closest evacuation site did not correspond to the one calculated by the EENT. This was done so that participants who make their decision primarily based on distance do not automatically select the evacuation site identified by the tool. The assumption was made that participants would mostly only select the evacuation site chosen by the tool if they were aware of the most influential key factor for that scenario.

For scenario 1 (District 1), a starting point was chosen that is located near rivers (see Figure 18). The decisive factor for this scenario is the type of roads, specifically bridges, which should not be crossed after an earthquake due to their instability. To reach the nearest evacuation site A, participants would have to cross a bridge, while the evacuation site selected by the tool (B) can be reached without crossing a bridge. Out of the evacuation sites B and C, B displayed a shorter evacuation time and was thereby chosen.

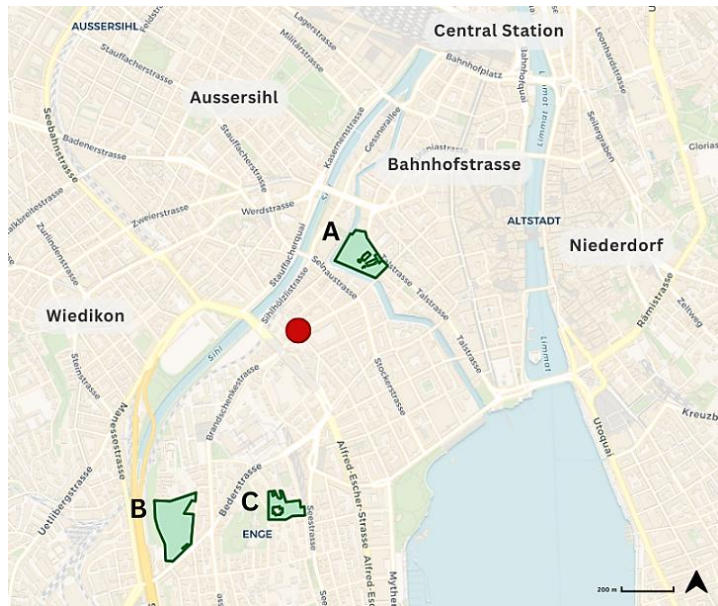


Figure 18: Map for decision-making task for scenario 1 (District 1), the red dot marks the starting point, the possible evacuation destinations are marked in green. The evacuation site chosen by the tool is destination B.

For scenario 2 (Industriequartier), the starting point was chosen in an area which is strongly influenced by soil amplification of seismic waves (see Figure 19), which is the decisive factor for this scenario. The closest evacuation site B lies in an area with high amplification of seismic waves, whereas the evacuation site chosen by the tool (C) lies in an area with lower amplification of seismic waves. The third evacuation destination (A) can only be reached via a bridge and was thus eliminated as an option. This led to evacuation site C being the fastest accessible location.

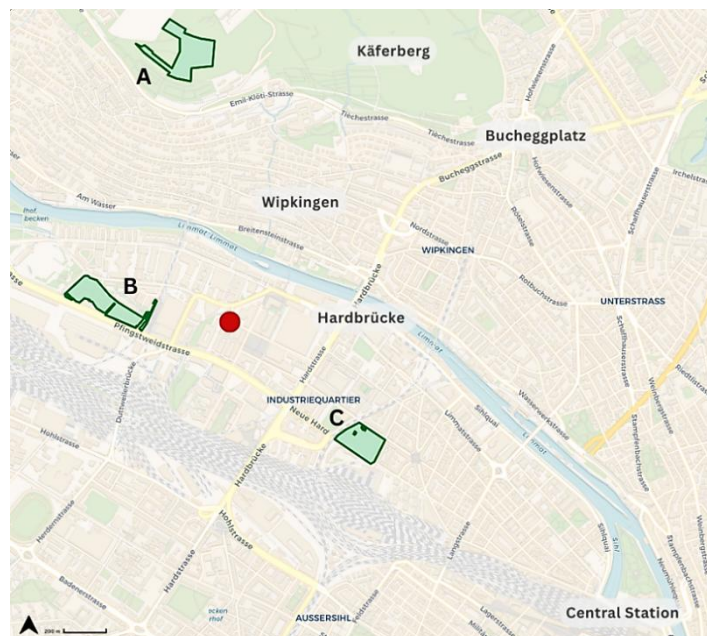


Figure 19: Map for decision-making task for scenario 2 (Industriequartier), the red dot marks the starting point, the possible evacuation destinations are marked in green. The evacuation site chosen by the tool is destination C.

For scenario 3 (Oerlikon), the starting point was chosen in an area that exhibits a large spatial difference in population densities during daytime versus nighttime (see Figure 20). The decisive factor for this scenario is thus the spatial population density. The reason for this difference in densities is that the location is close to the Irchel campus of the University of Zurich, which, with approximately 10'000 students and employees, is one of the largest university campuses in the city (Van Wezemaal & Nyfeler 2018). Evacuation points A and B are directly adjacent to the campus, which would likely lead to not only these evacuation sites becoming overcrowded but also the roads leading to them becoming heavily congested with university members in the event of an evacuation. For this reason, the tool computed evacuation site C as the fastest evacuation location. This spatial scenario near the university is further a suitable location, as it was assumed that many university members of this campus would complete the survey, thereby enabling an investigation into the extent to which familiarity may influence decision-making.

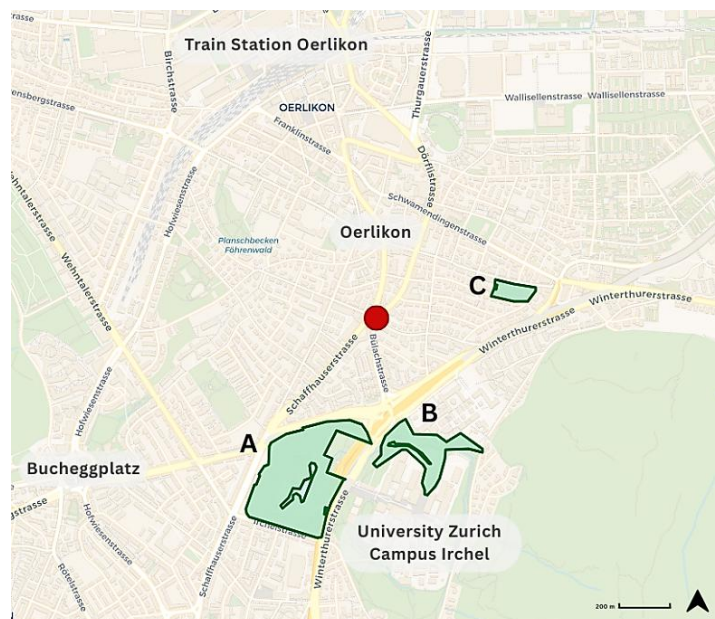


Figure 20: Map for decision-making task for scenario 3 (Oerlikon), the red dot marks the starting point, the possible evacuation destinations are marked in green. The evacuation site chosen by the tool is destination C.

As mentioned before, the participants were not informed about these key factors; instead, they had to make their decision based solely on the map excerpt and the information they could extract from it. To understand their choice of evacuation destination, they had to explain in an open-ended question their reasoning for selecting that evacuation site. Moreover, participants had to rate their confidence in their choice on a 5-point Likert scale. This was done as confidence works as a variable to assess the level of uncertainty regarding one's own decision for an evacuation location. It helps to prevent participants from simply choosing a random location,

but rather to choose the evacuation site they are most confident about (Wood et al. 2021). Finally, participants had to argue if and how they would change their decision, if the scenario were to happen at night.

In the last part of the survey, participants were shown the evacuation sites and routes calculated by the evacuation tool (see Figures 21 – 23). The participants were explained the key factors that led to this result as well as the underlying logic of the tool’s functionality.



Figure 21: Selection of evacuation site and route calculated by the tool for the decision-making task for scenario 1 (District 1)

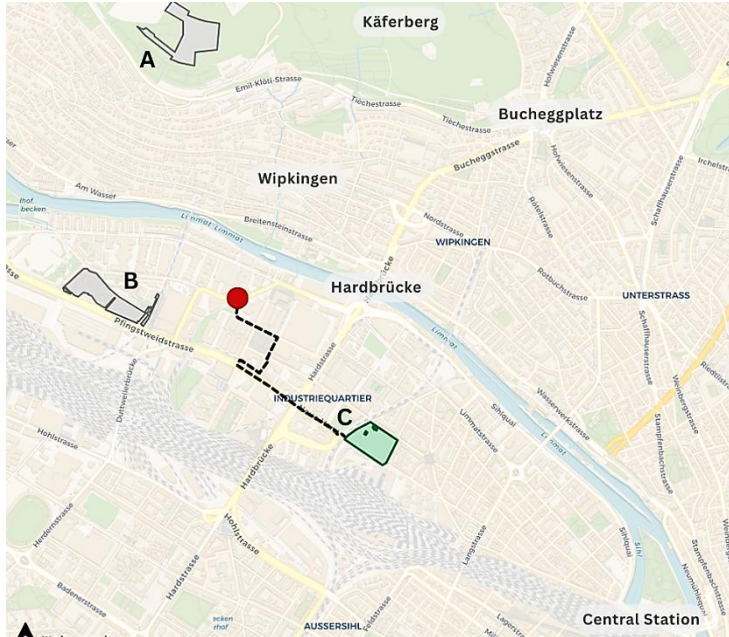


Figure 22: Selection of evacuation site and route calculated by the tool for the decision-making task for scenario 2 (Industriequartier)

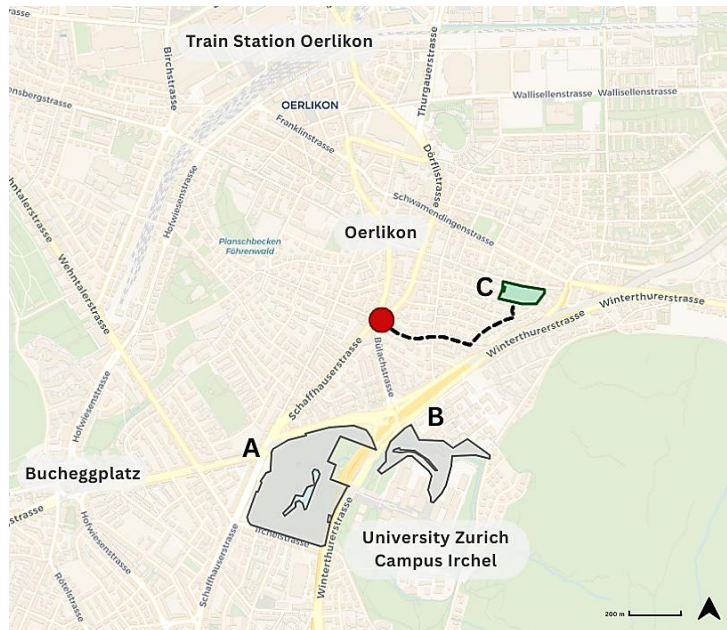


Figure 23: Selection of evacuation site and route calculated by the tool for the decision-making task for scenario 3 (Oerlikon)

Based on their knowledge of how the tool calculated evacuation maps, the participants then answered questions about their perception of the tool as well as if they believed the tool could support them in a real emergency. Participants first had to rank all factors used to calculate evacuation routes and destinations according to their personal perceived importance on a 5-point Likert scale. They also had to answer whether they had taken these factors into account when choosing the evacuation site in the main part of the survey. They could answer with “Yes,” “Partially,” or “No” for each factor. This was followed by three questions about the perception of the tool, which addressed the participants’ perceived helpfulness, trustworthiness, and the feeling of security of the tool. All questions were answered using a 5-point Likert scale, ranging from low to high levels of these aspects. In addition, participants had to answer if they would rather use the tool, their instinct or both in a real earthquake evacuation situation. Participants were further asked whether factors for calculating evacuation routes were missing and, if so, which ones. They were subsequently asked where they perceived potential shortcomings or weaknesses in the tool. Both questions were open-ended. Finally, participants could leave an optional comment or question.

3.2.3 Execution of Survey

The finished survey was composed in both German and English in order to accommodate as many participants as possible. Participants could change the language in Limesurvey itself as they wished. The survey could be completed on any device. Before distributing the survey, a

pilot run was conducted with two participants to identify any potential comprehension or structural issues. Apart from a few minor spelling mistakes, the survey was not modified further and was ready for use.

The survey was then distributed via the communication channels of Instagram, WhatsApp, and email. In a first step, the author's friends and family were invited to participate. In a second step, a broadcast email was sent to all employees and students of the Department of Geography of the University of Zurich, briefly explaining what the survey was about and inviting them to participate. The survey ran for two weeks, after which the results were saved in CSV and PDF formats.

3.2.4 Analytical Methods

The survey yielded both quantitative and qualitative data, which can be examined using various analytical methods. Quantitative data analysis is performed by using descriptive or inferential statistics. Descriptive statistics describe data characteristics such as means, distributions or extreme points, whereas inferential statistics reveal relationships or patterns within the data by testing hypotheses (Field 2018). Qualitative data can be analysed deductively or inductively (Mayring & Fenzl 2019). In a deductive analysis, the survey answers are categorised into groups based on a theoretically grounded category system. First, prominent categories are identified in the literature, then, in a second step, the responses collected in the survey are assigned to these categories. This allows determining whether the survey responses display a similar pattern to those from the existing research (Mayring & Fenzl 2019). Inductive analyses define categories only based on the qualitative data collected. Thus, answers are categorised into groups that occur frequently in the data material (Mayring & Fenzl 2019).

4 Results

4.1 Navigation Tool

The developed navigation tool as well as all used datafiles and Python scripts can be found on GIT [here](#). The exact layout is explained in the README file.

Figures 24 to 26 display three sample maps resulting of the EENT to an evacuation site, a hospital and a custom point respectively. They were all calculated for the daytime scenario of a magnitude 6 earthquake and have the same start point in Zurich's District 1.



Figure 24: Resulting evacuation map from the EENT based on user input of a daytime earthquake with magnitude 6, with starting point in District 1 and destination type of an evacuation site

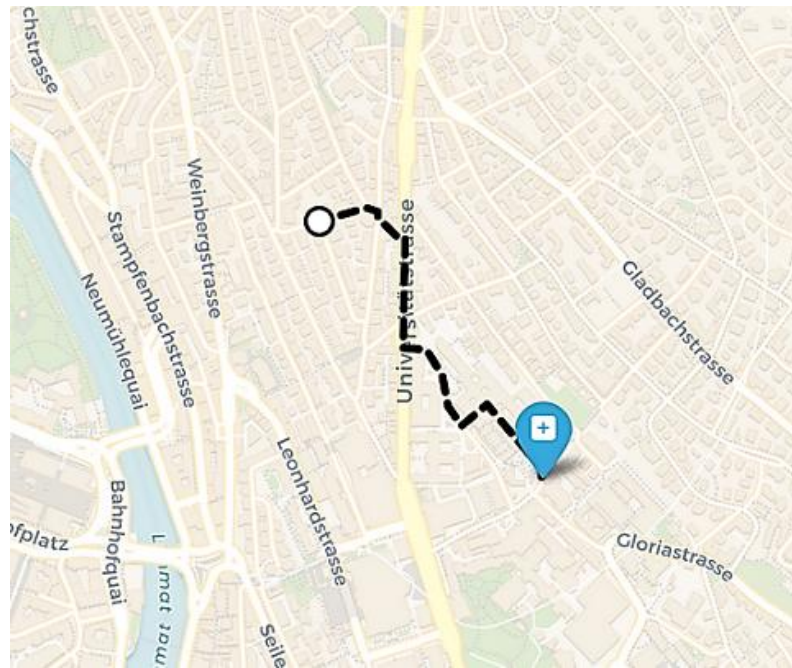


Figure 25: Resulting evacuation map from the EENT based on user input of a datetime earthquake with magnitude 6, with starting point in District 1 and destination type of a hospital

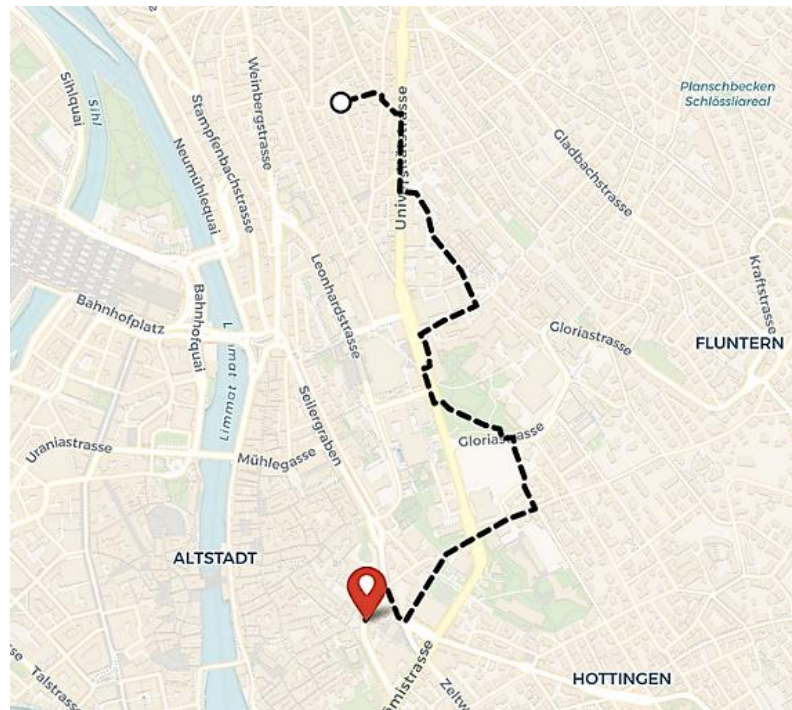


Figure 26: Resulting evacuation map from the EENT based on user input of a datetime earthquake with magnitude 6, with starting point in District 1 and destination type of a custom point

4.2 Survey

4.2.1 Sociodemographics

136 people participated in the survey. Out of those, 135 yielded viable answers, as one person wrote a comment that they misunderstood the questions. Gender-wise slightly more women completed the survey with 59% female, 39% male and 2% other participation. In the age range most people were between 18 – 29 years old (64%), followed by 30 – 44 years old (19%), 45 – 59 years old (10%) and 60+ years old (7%). About two thirds of the participants had either a bachelor's, master's or PhD degree, and one third of the participants had either done an apprenticeship or held a high school degree or other degree. Finally, 33% of the participants were living in the city of Zurich, whereas the bulk of the participants with 67% lived in other cities. Almost all participants lived in Switzerland except for three participants. The sociodemographic details can be seen in Table 2.

Table 1: Sociodemographics of the conducted survey (n = 135)

Sociodemographics		N	%
		n	%
1 Gender	Female	79	59
	Male	53	39
	Other	3	2
2 Age	18 – 29	86	64
	30 – 44	26	19
	45 – 59	14	10
	60+	9	7
3 Education	Apprenticeship	14	10
	High School (Matura)	28	21
	Bachelor	41	30
	Master	28	21
	PhD	22	16
	Other	2	2
4 Place of Residence	Zurich City	45	33
	Other	90	67

4.2.2 Knowledge about Earthquakes and Warning App Usage Levels

The distributions of the earthquake as well as local knowledge of Zurich display a central concentration, with most participants indicating their knowledge of the two variables being moderately good (3), followed by either good (4) or little (2) knowledge. The least number of responses are present in the extremes of very little (1) and very good knowledge (5). This can be seen in Figures 27 and 28. Earthquake and local knowledge exhibit mean values of 3.01 and 3.07, respectively.

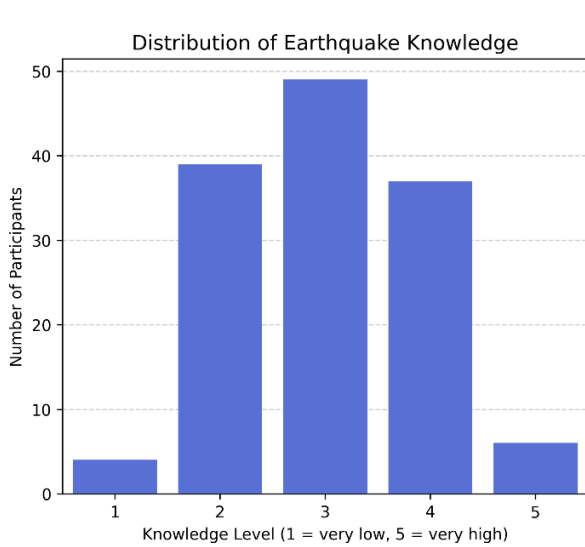


Figure 27: Distribution of earthquake knowledge ($n = 135$)

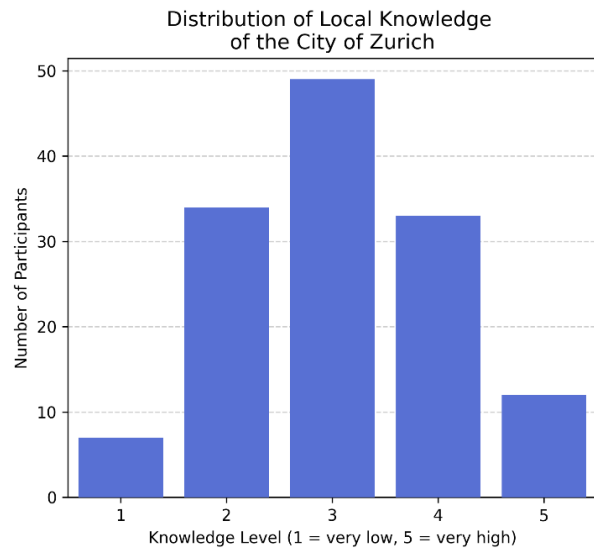


Figure 28: Distribution of local knowledge of the city of Zurich ($n = 135$)

Smartphone knowledge and trust were overall rated very high. For each participant, the median value across the three smartphone questions was calculated, which resulted in the majority having high knowledge and trust (4) in smartphones. The second most frequent response was very high knowledge and trust in smartphones (5). Only few participants indicate a moderate knowledge and trust in smartphones. No participants stated low (2) or very low (1) knowledge and trust in smartphones. The mean value of smartphone knowledge and trust is 4.36. This distribution can be seen in Figure 29.

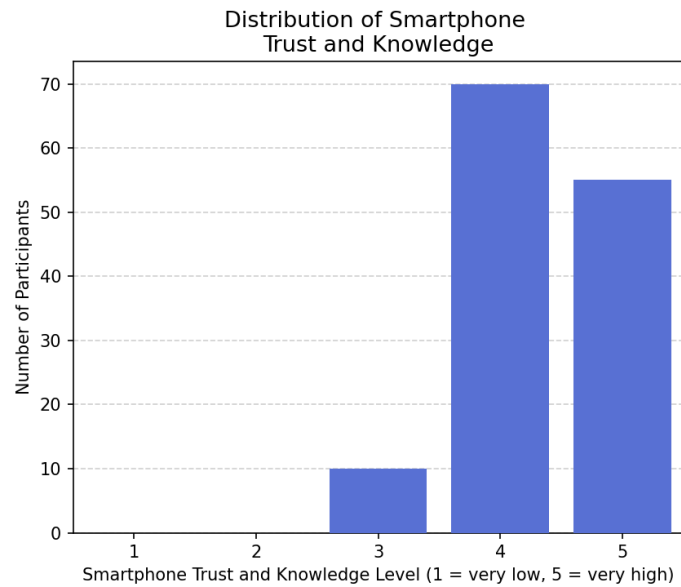


Figure 29: Distribution of smartphone trust and knowledge (n = 135)

84% of participants use warning apps, with the most prominent ones being MeteoSwiss, followed by Alertswiss and then Wetter-Alarm as well as other apps. 16% of participants do not use any warning apps (see Table 3).

Table 3: Warning apps usage distribution (n = 135)

Warning Apps Usage	N	
	n	%
Uses at least one app	114	84
MeteoSwiss	103	76
Alertswiss	44	33
Wetter-Alarm	12	9
Other	7	5
Uses no apps	21	16

4.2.3 Earthquake Reaction

To review the qualitative questions focusing on how participants react during or after an earthquake, a deductive analysis was conducted. For the question “How would you react if you were at home and a strong earthquake suddenly occurred?”, two prominent behaviours are described in literature. These are the following:

- Protective Shelter Seeking: to take cover under a sturdy object such as a table or a door-frame (Shapira et al. 2018, Blake et al. 2022)
- Immediate Self-Evacuation: to go outside and/or go to an open area (Shapira et al. 2018, Blake et al. 2022)

Based on these categories, the answers from the survey were classified accordingly. The distribution of responses can be seen in Table 4.

Table 2: Reaction during earthquake distribution (n = 135)

Reaction During Earthquake	N	%
Protective Shelter Seeking	79	59
Immediate Self-Evacuation	45	33
Other	10	8

For the question “How would you react immediately after an earthquake if many houses around you had collapsed?”, six prominent behaviours are described in the literature. These are the following:

- Altruistic Helping Behaviour: to help or find injured people (Ahmadi et al. 2024, Templeton et al. 2023)
- Environmental Assessment Behaviour: to react based on an assessment of the immediate environmental conditions, including factors such as debris, structural damage, human crowding and natural factors (Templeton et al. 2023)
- Following Behaviour: to either follow a crowd of people or follow instructions of an authority figure such as the government or rescue teams (Templeton et al. 2023, Sun et al. 2021, Ahmadi et al. 2024)
- Social Bond Behaviour: to contact or find significant close people like family members or loved ones (Templeton et al. 2023, Shapira et al. 2018, Blake et al. 2022)
- Defined Safe-Zone Behaviour: to move to a designated safe zone, such as an emergency meeting point or a shelter (Templeton et al. 2023)
- Panic-Driven Behaviour: to react panic-driven and/or irrationally (Sun et al. 2021)

Based on these categories, the answers from the survey were classified accordingly. Note that participants often described multiple reactions, which were then all counted. The distribution of responses can be seen in Table 5.

Table 3: Reaction after earthquake distribution (n = 135), participants could answer with multiple behaviours

Reaction After Earthquake	N	
	n	%
Altruistic Helping Behaviour	61	45
Environmental Assessment Behaviour	39	29
Following Behaviour	27	20
Social Bond Behaviour	18	13
Defined Safe-Zone Behaviour	10	7
Panic-Driven Behaviour	7	5
Other	10	7

4.2.4 Decision-Making Prior to the Introduction of the Tool

In the main section of the survey participants had to complete a task, in which they had to choose and argue for an evacuation site to evacuate to after a hypothetical earthquake. They had to do this for three spatial scenarios.

In all three scenarios, most of the participants did not choose the evacuation site that the tool identified as the optimal one to reach (see Table 6). In scenario 1, 53% chose site A, 31% site B, which was identified by the tool as the best option, and 16% site C. In scenario 2, the distribution is the most pronounced with site B being chosen by 84% of all participants. The second most chosen site is C, which was identified by the tool as the best option, with 12% and site A was chosen by 10% of all participants. In scenario 3, 74% chose site A, 16% site B and only 10% chose site C, which was identified by the tool as the best option.

The confidence level of choice for all scenarios is concentrated in between medium to medium-high confidence. Notably, the confidence level is highest for scenario 3, where the fewest participants selected the evacuation site calculated by the tool, and lowest for scenario 1, where the most participants selected the evacuation site calculated by the tool. Furthermore, only few people would change their decision if the scenario were to happen at three a.m. at night. Only 7% for scenario 1, 5% for scenario 2 and 3% for scenario 3 of participants would change their decision.

Table 6: Evacuation site choice distribution over the three scenarios in the survey task (n = 135). The site identified by the tool is coloured in blue. The confidence level displays the mean confidence of the participants' choice (1 = not confident at all, 5 = very confident)

Scenario	Site A		Site B		Site C		Confidence Level	Change if Night	
	n	%	n	%	n	%		n	%
Scenario 1	72	53	41	31	22	16	3.43	10	7
Scenario 2	10	7	113	84	12	9	3.54	7	5
Scenario 3	100	74	21	16	14	10	3.65	4	3

For all three scenarios, participants had to explain the reason why they selected the respective evacuation site. A deductive analysis was conducted for these qualitative answers. If given possible options to evacuate in a disaster situation, four prominent decision factors are described in literature. These are the following:

- Environment: to react based on an assessment of the immediate environmental conditions, including factors such as debris, structural damage, human crowding and natural factors (Templeton et al. 2023)
- Distance: to choose the evacuation point with the shortest distance (Bañgate et al. 2019)
- Evacuation Site Size: to choose the evacuation site with the biggest size (Bañgate et al. 2019)
- Familiarity: to choose the evacuation point / evacuation route one is the most familiar with (Sun et al. 2021)

Additionally, to these literature-based categories, an inductive qualitative analysis was carried out, where further categories emerged from the participants' responses. Firstly, population density was mentioned multiple times as a positive factor. Participants argued that they were more likely to evacuate to an evacuation point if a higher number of people were there. Secondly, in the category of environment multiple scenario-specific subcategories could be determined inductively. The created inductive categories can be seen in the following list:

- Population Density: to choose the evacuation point with the highest number of people
- Bridge: to avoid routes that cross over or under bridges to reach an evacuation point (subcategory of environment)
- Street: to avoid routes that follow narrow or busy streets to reach an evacuation point (subcategory of environment)
- Water: to avoid routes that pass near bodies of water to reach an evacuation point (subcategory of environment)

- Buildings: to avoid routes along areas with high-density or tall buildings to reach an evacuation point (subcategory of environment)
- Height: to choose the evacuation point located at the highest elevation (subcategory of environment)

Based on the deductive and inductive categories, the answers from the survey were classified accordingly. Note that participants often described multiple reasons, which were then all counted. The distribution of responses for scenarios 1, 2 and 3 are represented in Tables 7, 8 and 9, respectively.

Table 7: Reason of evacuation site choice distribution for scenario 1 (n = 135)

Scenario 1: Reason of choice	N	
	n	%
Environmental factor	94	70
- Bridge	45	33
- Street	22	16
- Water	13	10
- Buildings	8	6
- Height	6	4
Distance	82	61
Site Size	21	16
Familiarity	8	6
Population Density	0	0
Other	4	3

Table 8: Reason of evacuation site choice distribution for scenario 2 (n = 135)

Scenario 2: Reason of Choice	N	
	n	%
Environmental factor	64	47
- Bridge	21	16
- Street	15	11
- Water	0	0
- Buildings	15	11
- Height	13	10
Distance	108	80
Site Size	11	8
Familiarity	8	6
Population Density	1	1
Other	8	6

Table 9: Reason of evacuation site choice distribution for scenario 3 (n = 135)

Scenario 3: Reason of Choice	N	
	n	%
Environmental factor	53	39
- Bridge	0	0
- Street	31	23
- Water	0	0
- Buildings	19	14
- Height	3	2
Distance	46	34
Site Size	64	47
Familiarity	39	29
Population Density	4	3
Other	4	3

Furthermore, a Mann-Whitney-U test was conducted to assess whether there is a relationship between the choice of an evacuation site and the participant's confidence in their decision. As confidence was measured on a Likert-scale, the non-parametric Mann-Whitney-U test was chosen. The null hypothesis (H_0) states that there is no relationship between these two variables, whereas the alternative hypothesis (H_1) states that a relationship exists. All subsequent statistical tests are based on these hypotheses of no recognisable relationship (H_0) and recognisable relationship (H_1). To examine the relationship between these two variables, the evacuation site choices were merged into two groups: participants who selected the same site, which the tool calculated and participants who selected another site.

The Mann-Whitney-U test indicated that for scenarios 1 and 2 no statistically significant relationship can be found between the choice of the site and the participant's confidence. However, for scenario 3, with a p-value of 0.008 the test indicated a significant relationship between the choice of the site and the participant's confidence. As displayed in Figure 30, participants that did not choose the calculated evacuation site exhibited a higher confidence than those that chose the calculated site.

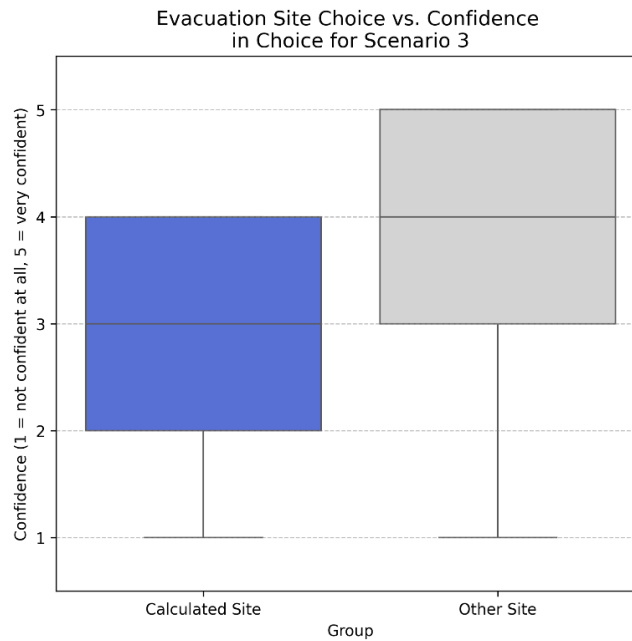


Figure 30: Evacuation site choice vs. participants' confidence in choice for scenario 3

Moreover, if participants stated that they would select another evacuation site if the scenario were at night, they had to explain their respective decision. Based on Glickman (1987), evacuees should consider the different distribution of the population density at night versus during the day and should thus avoid evacuation sites that are located in residential areas, which are likely to be overcrowded. Behavioural studies highlighted three additional key factors which can influence evacuation decision-making compared to daytime scenarios. These are the following:

- Light Source: At night, people have a tendency to move towards a light source to improve visibility (Zhang & He 2022).
- Herding Behaviour: At night, people rely more on others for orientation and are therefore more likely to follow groups or individuals (Zhang & He 2022).
- Familiarity: Reduced visibility increases uncertainty, leading people to prefer routes or destinations they are more familiar with (Sun et al. 2021, Zhang & He 2022).

Out of the 15 participants who indicated that they would choose a different site if the scenario were at night across all three scenarios, they most commonly only stated which other site they would select, but did not justify why. Only six participants also provided a reason as to why they would change their answer. Most notably, none of the participants provided population density nor familiarity as a reason; instead, light source and herding behaviour were the factors mentioned. This is summarized in Table 10.

Table 10: Factors to change the evacuation destination at night distribution (n = 15)

Factor to Change Evacuation Destination at Night	N	%
Light Source	4	27
Herding Behaviour	2	13
No Given Factor	9	60

In addition, a Mann-Whitney-U test was used to examine whether there was a relationship between the variables of earthquake knowledge, local knowledge or smartphone trust and knowledge, and the choice of the evacuation site. As the variables were measured on a Likert-scale, the non-parametric Mann-Whitney-U test was chosen.

For the test between local knowledge and choice of evacuation site, as well as smartphone trust and knowledge and choice of evacuation site, no statistically significant relationships were found in any of the scenarios. However, for the variable of earthquake knowledge and choice of evacuation site, a significant relationship was found with a p-value of 0.01 for scenario 1. The other scenarios, on the other hand, indicate no relationships. As can be seen in Figure 31, participants that chose the same site calculated by the tool, displayed a higher earthquake knowledge in scenario 1.

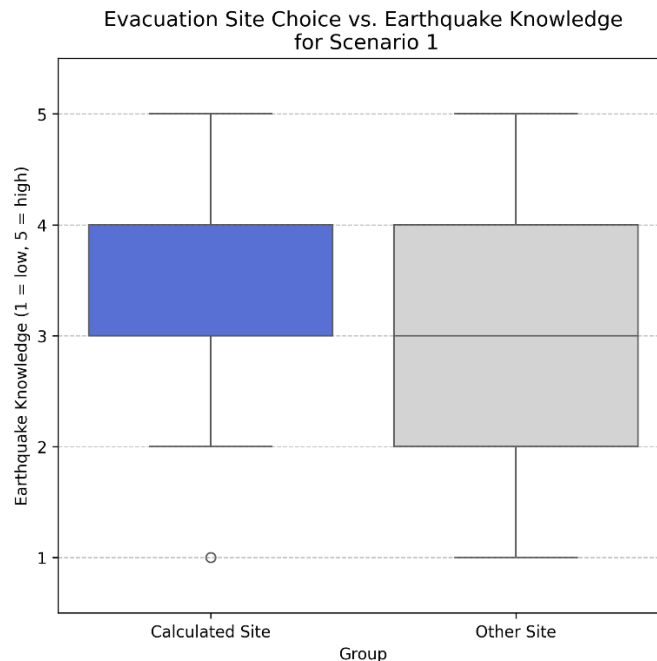


Figure 31: Evacuation site choice vs. earthquake knowledge for scenario 1

Finally, it was assessed whether there is a relationship between the participants’ age or education and their choice of evacuation site by using a chi-square test of independence, as both variables are categorical. No significant relationship was found between the participants’ age group and their choice of evacuation site, nor between the participants’ highest education and choice of evacuation site.

4.2.5 Perception of the Tool

After introducing the tool, participants had to indicate how important they rated the main factors which were used to calculate the evacuation routes and destinations. Importance was measured on a Likert scale ranging from 1 (“not important at all”) to 5 (“very important”). The factor *type of road* received the highest importance rating with a mean value of 4.67, followed by *collapse risk of buildings* with a mean value of 4.56. Both variables mainly received “very important” ratings. *Soil amplification* and *population density* received mean importance values of 3.87 and 3.77, respectively, with the bulk of the ratings being “important”. The lowest importance ratings were given to the factors *traffic density* and *time of the day* with mean values of 3.45 and 3.33, respectively, where the ratings “important” and “moderately important” were the most prominent. This distribution pattern is displayed in Figure 32.

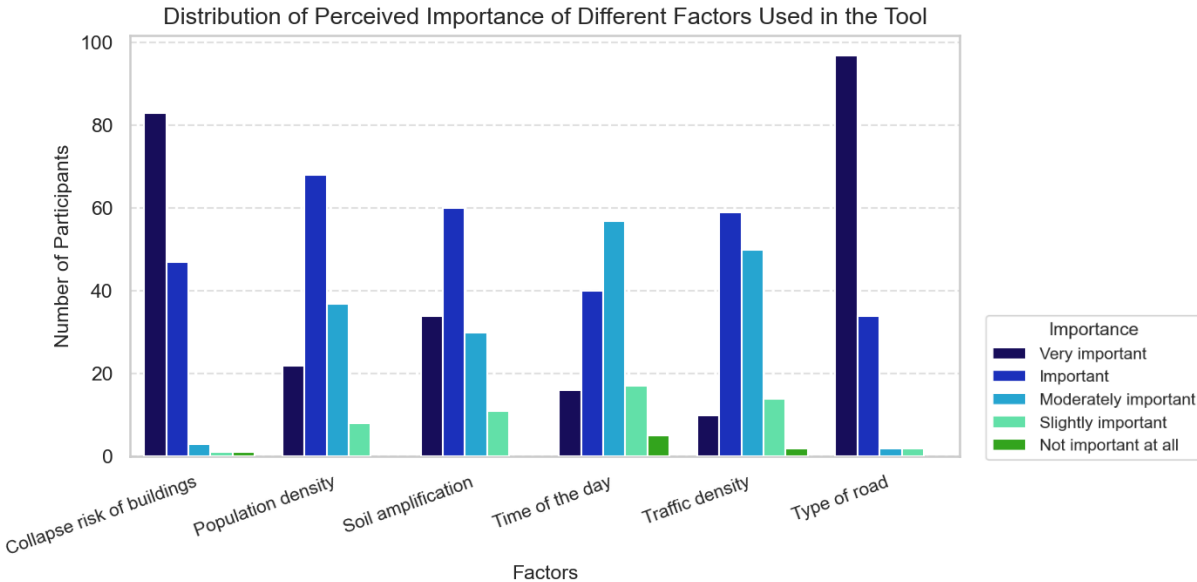


Figure 32: Distribution of perceived importance of different factors used to calculate the evacuation routes and destinations (n = 135)

Moreover, participants were asked whether they considered these factors while deciding for an evacuation site in the task. The largest share of participants considered the *type of road* and *collapse risk of buildings* with 50% and 40% of all participants, respectively. Additionally, 24% of the participants considered the *type of road* and 32% the *collapse risk of buildings* partially. The rest of the participants did not consider these factors when deciding for an evacuation destination. In contrast, for the factors of *population density*, *traffic density* and *soil amplification*, the majority of participants did not take these into account when making their decision. 62% did not consider the *population density*, 73% did not consider the *traffic density* and 89%, the highest percentage, did not consider *soil amplification* when deciding on an evacuation site. Figure 33 shows the distribution pattern of the consideration of different factors.

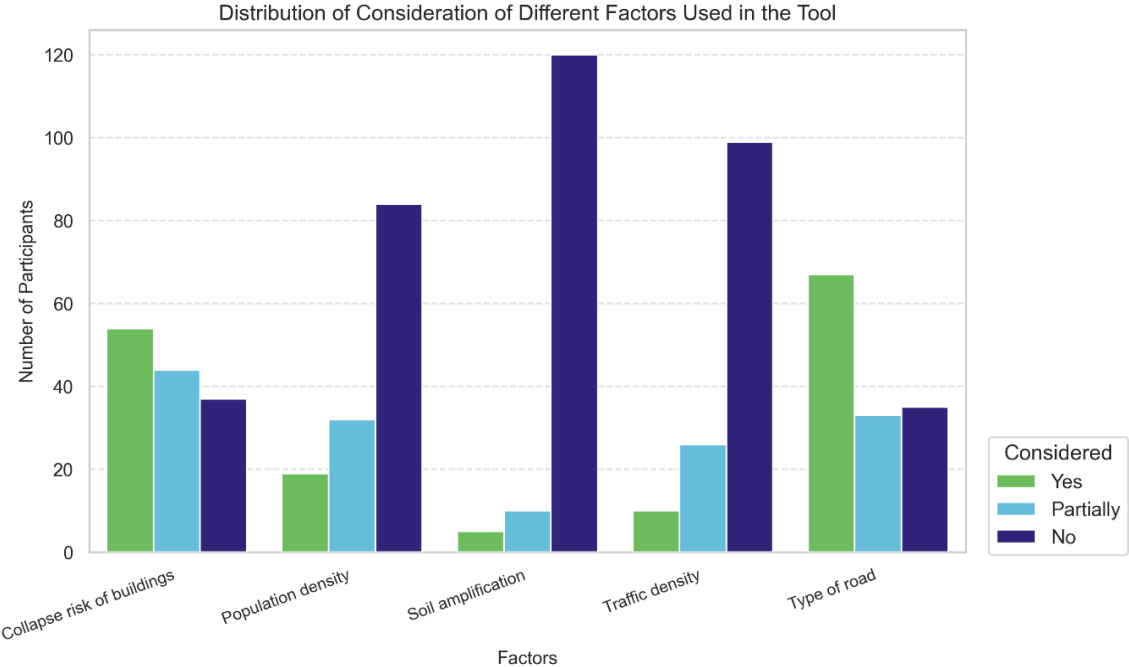


Figure 33: Distribution of the consideration of different factors used to calculate the evacuation routes and destinations (n = 135)

Using a Kruskal-Wallis test it was assessed whether there is a relationship between the perceived importance of the factors and the age group of the participants. This was done to see whether different age groups perceive certain factors in calculating evacuation routes as more important. Out of all surveyed factors only the factor of *time of the day* has a statistically significant relationship with the participants age group, displaying a p-value of 0.02. However, when applying a Post-Hoc Mann-Whitney-U test (Bonferroni correction) to analyse which age group(s) display a relationship with the perceived importance of the *time of the day* factor, no groups indicated a statistically significant relationship.

In addition, it was also assessed whether there is a relationship between the consideration of factors and the age group of participants. This was also done using a Kruskal-Wallis test. Out of all the surveyed factors only the factor of *traffic density* indicated a statistically significant relationship with the age group of the participants, displaying a p-value of 0.04. Here as well, a Post-Hoc Mann-Whitney-U test (Bonferroni correction) was conducted to test which age groups present significant relationships with the considered factor of *traffic density*. However, no statistically significant relationship with *traffic density* was found for any age group.

Moreover, participants had to rate the helpfulness of the tool as well as the trust in the tool on a Likert scale from 1 (“not helpful” / “no trust at all”) to 5 (“very helpful” / “complete trust”). This resulted in a mean helpfulness of 4.23 and a mean trust of 3.80. For both variables, values spread from 1 to 5, with a distinct peak at 4 (“helpful tool” / “strong trust in tool”). Using a Kruskal-Wallis test it was also tested for both variables whether there is a relationship to the age groups, however no statistically significant relationships were found. Thus, this indicates that participants’ perceptions of the tool’s helpfulness or trustworthiness do not differ across age groups.

Participants also rated how safe they would feel when using the tool in an evacuation situation on a Likert scale from 1 (“not safe at all”) to 5 (“completely safe”). Here, too, the mean value lies in a similar range as before at 3.62, with the participants’ answers displaying a spread across all values and a peak at 4 (“very safe”). In addition, no relationship between the age group and the feeling of safety when using the app was found here either when using a Kruskal-Wallis test.

Finally, when asking participants whether they would rather use the tool, their instinct or both in a real earthquake evacuation situation, over half of all participants argued that they would use both, followed by participants that would only use the app and finally participants that would only use their own intuition. This distribution can be seen in Table 11.

Table 11: Use of intuition versus tool during an earthquake evacuation (n = 135)

Intuition vs. Tool	N	
	n	%
Tool	31	23
Intuition	27	20
Both equally	77	57

4.2.6 Possible Shortcomings of the Tool

In the final part of the survey, participants had to argue what possible problems or shortcomings they perceived in the tool. Specifically, they were asked whether important factors when calculating the evacuation routes and destinations were not considered. To analyse this qualitative data a deductive analysis was conducted based on key aspects identified in literature, which were not included in the tool. These are the following:

- Mobile Network: The stability of the mobile network might be compromised due to the high user traffic or physical damage caused by the earthquake, which could make the app unusable (Ling et al. 2009).
- Data Currency: To provide the best possible evacuation routes the tool should use up-to-date data. Outdated data may lead to suboptimal or unsafe route recommendations (Jotshi et al. 2009).
- Panic Effect: After an earthquake, people may panic and forget to consult or properly use the tool (Sun et al. 2021).
- Accessibility Data: The tool should incorporate accessibility data, such as slope, stairs or surface conditions to support people with mobility restrictions, such as people with impairments or older adults (Chen & Cheng 2020).
- Shelter Capacity Management: Evacuees should be distributed evenly across parks to ensure that the capacity of the parks is not exceeded, and no overcrowding occurs (Ling et al. 2009).

Moreover, while assigning the responses to the before-mentioned groups, another inductive category was identified which has not yet been widely discussed in the literature. This is the following:

- Additional Emergency Information: The tool should provide further emergency information, such as where to find assistance, how to stay calm and current news about the earthquake.

Based on the deductive and inductive categories, the answers from the survey were classified accordingly. Note that participants could describe multiple shortcomings or no shortcomings at all. In total 121 shortcomings were described, which are displayed in Table 12.

Table 12: Shortcomings and problems in the tool perceived by participants (n = 121)

Shortcomings and Problems of the Evacuation Tool	N	%
Mobile Network	40	33
Data Currency	20	17
Panic Effect	13	11
Accessibility Data	9	7
Shelter Capacity Management	9	7
Additional Emergency Information	10	8
Other	20	17

Other shortcomings and problems that had been described include the potential for individuals not to have their smartphones with them during an earthquake, thereby preventing them from using the tool, the availability of the necessary data not being guaranteed in all countries, and the requirement for events with large crowds, such as concerts, to also be taken into account.

5 Discussion

This chapter addresses the three research questions outlined in the introduction and presents an extensive discussion of the corresponding findings. Subsequently, the limitations of the thesis are identified and their implication on the results is discussed. Finally, possible areas for further research are examined, emphasising how EENTs represent a promising tool for reducing earthquake casualties in the future.

5.1 RQ1: Modelling Earthquake Complexity

To answer research question 1, “*How can earthquake evacuation navigation tools model the complexity of an earthquake and its impact?*”, both literature-based approaches to modelling earthquake impacts and the methodology applied to develop the EENT in this thesis are discussed.

Earthquakes cause a widespread area of destruction, the effects of which can vary significantly across space (Barone & Mocetti 2014). As these impacts are not distributed homogeneously but heterogeneously, it is difficult to assess to what extent infrastructure, mobility and evacuation conditions are spatially affected (Kanamori & Brodsky 2004, NAZ 2004). To address this challenge, existing research has focused on modelling the impact of earthquakes indirectly through the vulnerability of infrastructure. Central to this approach is the vulnerability model developed by Cova (1999), which conceptualizes the damage risk of earthquakes as a function of hazard type and vulnerability of exposed infrastructure. Based on the infrastructure's structural integrity the probability of infrastructure collapse for different earthquake strengths can be calculated. The model thus abstracts the impact of an earthquake with the destruction vulnerability of infrastructure. In addition, the inclusion of the spatial road network as well as population distribution is a key factor in modelling the impact of earthquakes, thereby demonstrating how severely mobility and individuals are affected by the disaster (Southworth 1999). These approaches, which simplify the complexity of an earthquake down to the spatial extent of damage and its impact on mobility and human patterns, are widely used in developing earthquake evacuation models (Shimura & Yamamoto 2014, Tsionas et al. 2016). Building on these approaches, the EENT developed as part of this thesis combines these hazard-dependent vulnerability and contextual factors into a coherent tool that models the spatial impacts of earthquakes. In addition, the model incorporates the soil amplification of seismic waves, representing a novel approach that enables an improved modelling of the heterogeneity of earthquake impacts. While existing models assume a homogeneous impact of an earthquake, the proposed model thus

allows the capturing of spatially differentiated impacts based on local amplification or attenuation of seismic waves.

When it comes to modelling characteristics and impacts of earthquakes, GIS offers great potential. It allows various spatial factors to be calculated and combined using an MCE, thereby visualising the influence of different effects of an earthquake. Moreover, it allows the computation of interactions between factors, such as how roads can be blocked by debris from collapsed infrastructure or how soil amplification can spatially influence the strength of effects.

Nevertheless, earthquakes often present additional layers of complexity that have not yet been accounted for by earthquake models and tools. Secondary effects such as floods, landslides or fires can significantly exacerbate the destruction caused by earthquakes, however, they are highly unpredictable and location-specific. In addition, infrastructure failures such as blackouts or explosions at petrol stations represent extreme risks (Chen & Cheng 2020). Moreover, the spatial data used in earthquake models is often outdated or incomplete. This leads to major uncertainties in calculating the impact of earthquakes. Real-time information immediately after an earthquake that indicates the actual extent of damage is only rarely available, yet it holds great potential for further improving earthquake models (Ghafoori et al. 2022).

For these reasons, earthquake evacuation models and tools, including the EENT developed in this thesis, are only abstractions of reality. Due to the unpredictability surrounding all potential impacts of an earthquake and their uncertain spatial patterns, capturing the full complexity of an earthquake is not yet possible. Instead, the effects of earthquakes are highly generalised and simplified assumptions are required to ensure the implementability for such models. EENTs therefore represent a balance between complexity and feasibility. In addition, the empirical validity of EENTs is limited as major earthquakes rarely occur in locations where detailed models have been developed in advance. Thus, only little research has been conducted into comparing existing earthquake models with the actual impacts of real earthquakes.

Overall, RQ1 can be answered by concluding that EENTs exhibit significant potential for modelling the complexity and impact of earthquakes, particularly through the use of GIS. However, due to the high degree of uncertainty associated with earthquakes, data quality, as well as the difficulty of modelling secondary effects, EENTs should only be interpreted as a decision-support system, rather than exact representation of reality.

5.2 RQ2: Evacuation Routes and Destinations

To address research question 2, “*How can earthquake evacuation navigation tools determine optimal evacuation destinations and routes?*”, this section discusses how evacuation routing can be conceptualised using optimisation models and how the EENT computes evacuation routes based on the minimization of evacuation time.

The findings of this thesis demonstrate that determining optimal evacuation routes and destinations is inherently subjective and depends on the objectives and assumptions underlying the chosen model. There is no overall best solution as different models emphasise different goals, leading to specific advantages and disadvantages (Naghdi et al. 2008). Nevertheless, the most crucial objectives that evacuation optimisation models typically aim to achieve are either the calculation of the fastest or the safest route possible. These two objectives frequently conflict each other, as fast routes under normal conditions may not be safe under post-earthquake conditions and vice versa. In the development of such optimisation models, Southworth's (1991) network approach has established itself as a key principle. Within this framework, road networks are represented as networks consisting of edges and nodes, with each edge being influenced by a combination of hazard, vulnerability and contextual factors (Jotshi et al. 2009, Ling et al. 2009). This approach provides a robust structure for developing EENTs, whereby the selection of factors and choice of computational method have a major influence on the resulting evacuation routes.

In this thesis, optimal evacuation routes are defined as routes with the shortest evacuation time. Evacuation time depends on distance as well as environmental and contextual factors, including road attributes, debris from collapsing infrastructure, population density, traffic density and soil amplification. Aggregating these factors into a single value results in the evacuation time per edge in a post-earthquake scenario. Using Dijkstra's shortest path algorithm, the optimal evacuation routes and destinations are then calculated (Dijkstra 1959). By combining spatial distance and the impacts of an earthquake, the EENT thus aims to balance evacuation speed and safety. Compared to other optimisation models, the evacuation time-based model demonstrates many advantages. While Pareto-based models often involve trade-offs between multiple criteria, lack of adaptability in adjusting calculations, and exhibit low transparency (Shimura & Yamamoto 2014, Tsionas et al. 2016), the evacuation time approach enables flexible adjustments to calculations and offers high transparency, as the influence of individual factors can be tracked. In addition, the proposed EENT allows a user-based selection of parameters, including earthquake magnitude, time of day, starting point and destination type. Unlike existing models,

which rely on static scenarios with predefined parameters, the tool allows evacuation routes and destinations to be personalised and adapted to the extent of the disaster. This novel approach thus demonstrates potential for generating evacuation routes that better reflect real-world conditions.

Despite the advances in evacuation routing research, several challenges remain. Factors such as road accessibility for individuals with mobility restrictions are rarely incorporated into evacuation modelling, despite their importance in inclusive evacuation planning (Chen & Cheng 2020). Personalised routes, where the presence of accessibility features (such as stairs or steep roads) can be specified, thus represent a promising potential. Additionally, the capacity of evacuation sites, although frequently mentioned in existing research, cannot yet be implemented at large scale due to the high computational power required (Ling et al. 2009). Moreover, most evacuation models do not account for human evacuation behaviour tendencies, such as route familiarity, group dynamics, altruistic behaviour or the effect of panic (Ahmadi et al. 2025, Templeton et al. 2023). Limited empirical research has been conducted linking human evacuation behaviour with the development and design of EENTs.

Overall, RQ2 can be answered by concluding that evacuation routes and destinations are determined through subjectively defined optimisation models reflecting individual objectives. By minimizing evacuation time in the proposed EENT, an approach is presented which aims to balance safe and fast routes while remaining a transparent and adaptable computation process.

5.3 RQ3: Potential for Human Decision-Making Support

To address research question 3: “*How can earthquake evacuation navigation tools support users in evacuation decision-making?*”, the results of the survey are compared and discussed in relation with established concepts and findings from existing literature on evacuation behaviour research. In this process, the proposed hypotheses are critically evaluated. Firstly, typical human earthquake evacuation behaviour without digital navigation aids is analysed. Subsequently, the evacuation decision-making support potential of the proposed EENT is explored.

5.3.1 Human-Based Earthquake Evacuation Reaction

Behaviour During and Post-Earthquake

The reported behaviours during an earthquake align largely with those found in literature (Blake et al. 2022, Shapira et al. 2018), with participants stating that they would mainly seek shelter under sturdy furniture or leave buildings to go to open spaces. Beyond the reaction during an earthquake, the participants’ post-earthquake behaviour also reflects behaviour patterns

described in the literature. Most notably, social behaviours emerge as primary reactions, including altruistic helping behaviour, following behaviour and social bond behaviour. This reflects the importance of social factors and group dynamics, which are considered key drivers of evacuation behaviour (Ahmadi et al 2025, Zhang & He 2022). Moreover, panic-driven behaviour is mentioned by a subset of participants, reflecting the stress-induced influence on the cognitive decision-making process. This underscores the literature-based finding that panic is a common experience following an earthquake (Templeton et al. 2023, Drury et al. 2023). In contrast, logic-based evacuation approaches to ensure personal safety, such as the environmental assessment method and defined safe-zone behaviour, are mentioned less frequently. This supports previous findings stating that people in disaster situations are often overwhelmed and lack the cognitive capacity to take rational decisions. Rather, they tend to make decisions based on emotions and social impulses (Blake et al. 2022, Sun et al. 2021).

Evacuation Site Selection in Simulated Earthquake

When asked to select an evacuation site in a simulated earthquake scenario participants rarely selected the same evacuation site that was calculated by the EENT. Instead, evacuation decisions were primarily influenced by environmental factors, distance, the capacity of the evacuation site and familiarity with the location. This highlights the discrepancy between human evacuation behaviour and the optimisation-based modelling of evacuation routes and destinations (Chen & Cheng 2020).

In scenario 1, most participants chose the same evacuation site as the EENT, compared to the other scenarios. Many participants stated that their decision was driven by their perceived risk of bridges collapsing, thus identifying infrastructural vulnerability as the most influential factor in calculating the evacuation route for this scenario. This indicates that human-based decision-making processes recognise infrastructural collapse as a distinct risk and therefore actively integrate it into evacuation considerations. In addition, both the distance to the evacuation site and the size of the site emerge as significant factors, suggesting that evacuation behaviour is dependent on both risk awareness and rational consideration regarding evacuation speed and site capacity.

In contrast, in scenario 2, participants focused primarily on distance, while other factors were given less importance. This implies that in the absence of an apparent environmental risk, distance emerges as the most important variable when choosing an evacuation destination. This supports the widely reported assumption that distance is a key heuristic in the evacuation decision-making process (Bañgate et al. 2019, Sun et al. 2021).

Scenario 3 offers additional insights into evacuation behaviour. Participants primarily selected evacuation sites in close proximity to the university campus and placed great importance on evacuation site size and familiarity. It is noteworthy that although site size was cited multiple times as an essential factor, many failed to consider that the proximity of these evacuation sites to the university would attract a disproportionate high number of evacuees, making overcrowding highly probable. This suggests that the capacity of evacuation sites may be factored in, though only in relation to spatial dimensions and not population distribution. In addition, familiarity emerged as a key decision factor, as most participants study or work at the university. These findings support the notion that with high levels of local knowledge, familiarity forms an essential key choice-factor. In this context, familiarity also appears to be closely related to social behaviour, as many participants stated that they hoped to meet people they knew at the evacuation sites near the university. This further underscores the immense importance of social relationships in evacuation situations. Additionally, a correlation between the evacuation site choice and confidence in choice was observed, with participants who selected the evacuation sites in proximity to the university reporting higher confidence. This suggests that familiarity not only influences the choice of evacuation site, but also confidence in the choice. This further emphasises the importance of this criterion. This may have also led to an overconfidence in choosing familiar locations, and thus a failure to critically assess their suitability as evacuation sites.

Moreover, across all scenarios, population density rarely emerged as a negative decision factor. Despite its central role in calculating evacuation routes and destinations to avoid congestion and overcrowding, participants seldom considered it when deciding on evacuation sites. This indicates that large crowds are not perceived as major risks in evacuations. Such perceptions are consistent with behavioural literature which state that people perceive crowds as a positive factor due to the herding instinct that occurs in high-stress situations (Templeton et al. 2023). This observed discrepancy between technical modelling and behavioural patterns highlights the importance of including human evacuation behaviour in the development of evacuation tools.

In addition, the findings indicate that the temporal influences of day and night only display a minimal influence on the evacuation site selection as solely few participants argued that they would change their decision if the scenario were to occur at night. The primary reasons why their decisions would change relate to finding evacuation routes with better lighting and evacuating to places with a higher presence of people. These findings are consistent with those of Zhang & He (2022), who argue that people feel less safe in the dark and thus are more likely to

seek light or contact with other people. This reveals a further mismatch between the modelling of evacuation routes and sites and human behaviour. In the EENT the time of the day influences how population densities are distributed, leading to evacuation routes avoiding areas with large numbers of people in order to prevent congestion. In the human decision-making process however, importance is placed on finding contact with other evacuees. This shows how cognitive-driven evacuation often places greater emphasis on social factors rather than logic-driven factors.

Demographic and Knowledge-Related Influences

Beyond behavioural patterns, the survey results also reveal differentiated insights into the relationships between demographic characteristics, knowledge variables and their choice of evacuation site. Contrary to findings reported in existing literature, no significant relationships were found between education level and choice of evacuation site or age and choice of evacuation site. A plausible explanation for this lies in the uneven distribution of both the age and education of the participants, with the majority of participants being young and highly educated. In addition, participants had to make their decisions based solely on a thought simulation of an earthquake rather than in a real-world scenario. This may have compromised the influence of demographic effects. Similarly, no significant correlation was found between the parameter of local knowledge and the choice of evacuation site. This implies that high local familiarity alone does not influence the choice of evacuation site. The influence of smartphone knowledge and trust is not discussed, as all participants indicated medium to high levels of knowledge, meaning that no statistically significant conclusions can be drawn.

In contrast, the choice of evacuation site and earthquake knowledge revealed a more diverse pattern. A significant relationship was found between the two variables in scenario 1, suggesting that people with greater earthquake knowledge are more likely to choose the same evacuation site as calculated by the EENT. This may be due to the significant impact of collapsing bridges in this scenario, which appears to be a well-understood risk of earthquakes. However, as this relationship is not apparent in scenarios 2 and 3, earthquake knowledge may be primarily related to the risk of collapse. Other risks related to population densities or soil amplification may be lesser known and therefore have little influence on the evacuation decision.

Discussion of Hypotheses

These findings allow the addressing of the proposed hypotheses. Hypothesis 1, “*Participants generally select the spatially closest evacuation site.*”, is largely supported by the survey results.

Across all scenarios, distance is shown to be an essential factor in deciding on an evacuation site, particularly in scenario 2. However, distance was rarely the sole determining factor; environmental hazards, evacuation site capacities, familiarity and social dynamics also play a crucial role, thus indicating that evacuation decisions are based on a combination of multiple factors.

Hypothesis 2, “*Participants with higher local knowledge are more likely to select an evacuation site they are familiar with*”, is addressed with differentiated results. Scenario 3 demonstrated that familiarity due to local knowledge can play a crucial role in evacuation site choice, even when other factors such as overcrowding are apparent. However, when local knowledge and evacuation site choice were directly compared, no relationship was identified. This suggests that the impact of local knowledge is situation-dependent and cannot be generalised into always leading to familiar places being chosen.

Hypothesis 3, “*Participants with higher earthquake knowledge are more likely to select the same evacuation site as the one calculated by the EENT*”, is partially supported. While high earthquake knowledge in scenario 1 can be significantly linked to the choice of evacuation site, this relationship is not apparent in the other scenarios. This indicates that earthquake knowledge regarding the structural integrity of bridges is generally more widely known while other factors are less widely known and therefore exert little influence in evacuation behaviour.

5.3.2 EENT Support Potential

Overall, the EENT was perceived helpful and trustworthy by participants. In addition, many participants felt that the tool provided a good sense of safety, highlighting the tool's potential for support. No significant differences in perceptions about the EENT were found across age groups, suggesting that the tool is assessed similarly regardless of age. This indicates that the tool is usable for the general population, rather than being tailored to specific demographic groups. However, it should be noted that the relatively homogeneous group of mostly young, well-educated participants does not fully represent the general population and may thus not necessarily reflect the public opinion. In general, most people stated that in a real-life situation they would follow both the EENT and their own intuition. These findings correspond with the literature-based importance of human evacuation behaviour, which emphasises personal risk perception and individual experience as crucial components (Eiser et al. 2012, Shapira et al. 2018). Completely giving up control is rare; rather, intuitive judgement remains an important component in high-stress situations, even when digital aids are available (Xie & Xu 1995).

In the perception of the individual factors underlying the EENT, the type of road (bridge/tunnel) and the risk of building collapse were rated as very important and further displayed the greatest influence on the participants' choice of evacuation sites. This reinforces earlier findings that seismic knowledge is most commonly associated with the risk of collapse of various infrastructure, which are therefore more likely to be taken into account in the decision-making process. Moreover, despite being perceived as important, factors such as traffic and population density, as well as soil amplification, were rarely considered in the selection of evacuation sites. This is an indication that there is a knowledge gap regarding these more complex and less intuitive factors. Due to the difficulty of visualising such abstract factors spatially and consequently integrating them in the decision-making process, digital tools show great potential to assist in this regard. By transforming intangible risks into concrete spatial factors in the EENT, often overlooked variables can be rendered accessible to evacuees. Furthermore, no significant relationships were found between the perception or consideration of individual factors and age group. Although some factors point to possible relationships, these are not apparent in more detailed analyses. Once again, the uneven distribution of age groups in the survey sample may explain these differentiated results.

Despite the overall positive perception of the EENT, participants also identified several shortcomings in the tool. The main concern relates to the potential failure of the mobile network in the event of an earthquake which could render the tool unusable. This limitation has been widely discussed in existing literature (Ling et al. 2009, Chen & Cheng 2020) and represents a fundamental challenge in EENTs. A possible solution would be for the tool to function completely offline, running on predefined datasets. However, this directly conflicts with another frequently mentioned limitation: the lack of up-to-date data. While highly current data, such as real time data, would improve the accuracy of evacuation routes, it would simultaneously render the tool vulnerable against mobile network failure. This displays an inherent trade-off between data currency and tool robustness, thus demonstrating the complexity of designing an EENT. Furthermore, participants frequently mentioned the lack of accessibility and evacuation site capacity data, which indicates that users are aware of the relevance of these variables. Beyond the technical aspects of the tool, many participants also expressed a desire for additional information to be integrated in the EENT. Rather than blindly trusting the tool, including explicit information regarding the nature of the earthquake, the reasoning behind the route and evacuation site selection as well as behavioural advice increases the transparency and credibility of the generated evacuation routes. Thus, the EENT should not only be a navigation aid but also a comprehensive source of information. Finally, the tool's lack of inclusion of the effect of panic

was also recognised as a limitation. Many participants argued that panic and emotional stress would prevent them from trusting the tool rationally. This indicates that evacuation tools should not only provide evacuation guidance but also psychological support by offering reassurance and reducing anxiety. This reinforces the notion that EENTs insufficiently account for human behaviour and that purely technical solutions lack appeal. It therefore underlines the need for EENTs to be designed with real evacuation situations in mind, serving not only as navigation aids but as comprehensive decision-making tools.

Considering these findings, RQ3 can be answered by concluding that EENTs demonstrate great potential in supporting the evacuation decision-making process. Due to the lack of institutional support for evacuees in the initial phase after an earthquake (NAZ 2004), EENTs show promise in assisting evacuees significantly throughout this phase. By visualising optimal evacuation routes and sites, the tool alleviates cognitive load. In doing so, it effectively removes two key stages in the high-stress decision-making process (Mohajeri & Mirbaha 2021): evacuation route and destination choice. Moreover, the simulated earthquake task clearly demonstrated that participants mostly failed to select optimal evacuation sites in a hypothetical scenario by frequently overlooking complex, spatial factors. This highlights the value of such digital decision-support tools. However, the findings also indicate that human-based behaviours are currently underrepresented in EENT-design. Social dynamics, familiarity, transparency, and the effect of panic are all critical decision-making factors, which are not yet incorporated in EENTs. For EENTs to have real-world value in actual disaster situations, they need to combine purely technical, logical factors with human characteristics. Not only should speed and safety be prioritised during evacuation, but human desires such as social connections and familiar evacuation site preferences should also be integrated.

5.4 Limitations

This thesis is subject to several limitations related both to the methodology of developing the EENT as well as the design and implementation of the survey. These limitations mainly relate to data quality, computational simplifications, modelling constraints and the demographics of the survey participants.

5.4.1 Data Quality

A major limitation of the EENT lies in the quality of the used data. Several datasets such as the height models or population density distributions were only available in low spatial resolutions. This leads to a reduced quality of the resulting evacuation routes as road sections are not

assigned their local values but instead the average of all values in the pixel in which they are located in. Consequently, evacuation routes are calculated based on generalised representations of aggregated areas rather than precise location-specific information.

Additionally, the building heights show significant inaccuracies, as they were derived based of the DTM and DSM, both of which have low spatial resolutions. Since the DSM not only includes the height of man-made objects but also areas that are not influenced by humans, for example the area surrounding a building, the calculated building heights are underestimated. As these heights are essential for calculating the debris area in the event of collapse, they compromise the accuracy of blocked roads.

Furthermore, with the data ranging from 2021 to 2025 not all used data are fully up to date. This may result in discrepancies between the representation of the circumstances in the EENT and reality. For example, it is possible that new roads or infrastructure have been built that have not been included yet in the data and thus are missing from the EENT.

Finally, the availability of datasets also represents a limitation. Several datasets were not publicly available, including accessibility data and data concerning secondary geological hazards, such as landslides. Due to the absence of accessibility data, that is stairs, slopes, kerb ramps or road conditions, routes cannot be adapted to accommodate people with mobility restrictions. Such information would be particularly important for people with walking impairments, elderly people or parents with strollers, to ensure safe evacuation. Moreover, the exclusion of secondary disasters such as landslides, despite their frequent occurrence in combination with earthquakes, are not considered. As these geological hazards can block roads and thereby render evacuation routes impassable, their omission can limit the reliability of the generated routes.

5.4.2 Computational Simplifications

Several simplifications were made in the computational process. The building collapse risk was calculated based solely on the year of construction and the number of floors, with factors such as building material, construction quality or type of building not taken into account due to lack of data. Although this approach is based on literature, it is only a highly simplified method of calculating infrastructural collapse risk and thus exhibits uncertainty.

In addition, the temporal distinction in population density was greatly simplified to a daytime and nighttime scenario. Peak travel times during mornings and evenings, as well as special periods such as weekends or public holidays, are not included. Moreover, the daytime

population density only includes the distribution of dayshift employed individuals and not students, retirees, unemployed people, or others who may be at home. The nighttime distribution assumes that all people are at home at night, neglecting night-shift workers or leisure-related activities.

Furthermore, as no direct data was available for traffic density, the proxy of traffic noise was used. Although traffic noise generally correlates with traffic density, variables such as speed limits, vehicle types or road surface conditions can also affect traffic noise, independent of traffic density.

Overall, the EENT requires high computational power due to the large number of spatial datasets and the complexity of the shortest path algorithm. This causes increased processing times, in particular for long evacuation routes. If the tool was further developed into an app which runs on smartphones, some computational processes may need to be simplified or optimised to ensure a consistent performance even on less powerful devices. Moreover, the factors of slope and capacity of the evacuation sites could not be incorporated into the EENT due to computational constraints. To integrate these factors, higher processing power as well as storage capacity would be needed. The lack of slope limits the accuracy of the evacuation time calculation as differences in walking time based on steepness are not considered. As a result, optimal evacuation routes may have steep sections that would take longer to traverse in reality compared to the computed time. Similarly, the lack of evacuation site capacity also limits the results of the EENT. The model selects evacuation sites regardless of how many other evacuees would also be directed to that site. This can lead to congestion and overcrowding at evacuation locations, leaving no capacity for the user.

5.4.3 Modelling Constraints

The modelling of evacuation routes is based on the parameters of starting point, time of day, earthquake magnitude and destination type, which must be defined by users themselves. However, if the EENT were to be used in a real-world scenario, manual entry of these criteria would be impractical. In particular, affected individuals are unlikely to know the magnitude of the earthquake immediately after it has occurred. Therefore, the user-based setting of these parameters in this thesis is only a conceptual approach to evaluate the feasibility and performance of the tool. In practical applications, it would be ideal if the starting point and time of the day could be set automatically using GPS and time settings of the smartphone, and the earthquake magnitude could be determined by integrating data from a local seismological station.

In addition, the modelling of evacuation time is based on the average walking time derived from non-disaster scenario. While this walking time is empirically grounded, it assumes a homogeneous population in which all individuals move at the same speed. Slower moving people, such as elderly adults or people with impairments, are therefore not explicitly accounted for. Furthermore, behavioural effects such as panic or shock, which can alter the basic walking speed, are also not factored in. Further research into movement speeds in evacuation situations would be required to allow these factors to be incorporated into the model.

5.4.4 Survey Demographics

Finally, the results of the survey are limited by the demographic composition of the participants. As the survey was primarily distributed within the author's field and at the University of Zurich's Department of Geography, the majority of respondents were educated, young individuals with strong technical affinity. In addition, as many geography students completed the survey, a high level of knowledge of cartography and geological processes such as earthquakes was present. This may have influenced the perceived helpfulness, trust and acceptance of the EENT. Consequently, the findings cannot be directly generalised to the broader population, especially older, less educated individuals, who were underrepresented in the survey.

5.5 Future Research

The findings in this thesis highlight several promising directions which can be explored in future research. A central area concerns the integration of human behaviour patterns in EENT research. Evacuation behaviour factors such as social dynamics, stress or familiarity could be incorporated into EENTs, allowing them to provide navigation that is more aligned with human reactions. Similarly, the personalisation of EENTs also demonstrates potential for combining human-dependent aspects with the technical modelling. Evacuation behaviour strongly depends on individual characteristics such as physical ability or situational constraints. People with limited mobility, for example, require evacuation routes that are well accessible. By including personal information about age, mobility impairments or the need to evacuate with other people, EENTs could be designed to be inclusive for different population groups.

Another possible future research field is to explore how real-time data can be integrated into EENTs to increase the accuracy of the routes generated. Dynamic changes in population or the ability to update blocked roads or obstacles in the tool in real time could greatly improve the relevance of the suggested routes. At the same time, however, EENTs should also be robust against mobile blackouts. A hybrid tool capable of combining these factors opens up exciting

possibilities for further research. Moreover, empirical validation of the generated evacuation routes and destinations in the form of field experiments points to further research opportunities. Real-world testing with, for example, weak simulated earthquakes can show whether the calculated impacts of the earthquake occur as predicted.

Finally, future research may focus on how EENTs can be developed into apps compatible with smartphones, thereby addressing challenges of computational power, app design and communicating transparency. To this end, studies must be conducted on the usability of the apps, specifically in high-stress situations. In addition, app developers need to identify ways to communicate relevant information transparently whilst clearly conveying uncertainties. Human-computer interactions are particularly critical in the context of emergency applications as such tools can directly affect people's safety and thus potentially influence the consequences of earthquakes.

6 Conclusion

This thesis set out to evaluate if and how EENTs can support affected individuals in the immediate aftermath following an earthquake. Building on existing literature, a proof of concept for a pedestrian EENT was developed which calculates and visualises the most optimal evacuation route to different destinations, including evacuation sites, hospitals or custom points. Unlike most existing approaches, the proposed EENT is user-oriented as it allows key parameters to be defined dynamically. The tool was subsequently evaluated in the form of a survey on its perceived helpfulness and functionality. The overarching aim of this thesis is to bridge the gap between technical evacuation modelling and real-world post-earthquake human behaviour.

With regard to RQ1, this thesis demonstrated that EENTs can model the complexity and impacts of an earthquake to a certain extent by combining various environmental and contextual elements of an earthquake through network-based modelling. Crucial factors for identifying the spatially heterogeneous impacts of earthquakes include vulnerability of infrastructure collapse, soil amplification of seismic waves, secondary disasters, and population and traffic densities. At the same time, the results also show that EENTs only remain abstractions of reality. Consequently, such tools should be understood as a decision support system rather than exact representations of earthquake dynamics.

RQ2 can be approached by concluding that evacuation routes and destinations may be determined through optimization models, combining vulnerability modelling with shortest path algorithms. However, optimal evacuation routes and destinations are inherently subjective and reflect individual goals. As a result, they are context-dependent and vary based on different scenarios. Nevertheless, optimisation models mostly seek to strike a balance between fast and safe routes, as was done in the developed EENT in this thesis by combining distance- and hazard-factors to derive a single evacuation time metric.

Addressing RQ3, the findings of this thesis showed that EENTs hold substantial potential to support affected individuals during earthquake evacuations. By visualising the optimal evacuation routes and destinations, evacuees are provided with assistance during the most critical phase following an earthquake, thereby reducing cognitive load. The results of the survey demonstrate that people often rely on intuition, social dynamics, familiarity or perceived risks in the evacuation decision-making process. In doing so, the influence of more abstract spatial effects such as population and traffic density or soil amplification is overlooked. Following the introduction of the EENT, many participants reported high confidence and perceived

helpfulness in the tool, underscoring its relevance as a supportive aid. Although participants would not necessarily abandon their intuition, they view the EENT as a valuable guidance tool in combination with personal assessment. At the same time, the survey results also indicate a demand for the integration of socio-personal dynamics, suggesting that EENTs should place greater emphasis on human-centred design.

Overall, this thesis contributes both methodologically and empirically to earthquake evacuation research by presenting a transparent and adaptable framework for pedestrian evacuation modelling and by evaluating user perceptions through a survey. Despite these contributions, limitations in the methodology were also identified, primarily relating to data quality, computational simplifications, modelling constraints and the low demographic diversity among survey participants.

Future research could build on this thesis by further integrating human behavioural patterns such as social dynamics, stress, or familiarity, or by exploring the possibility of demographic personalisation of the generated routes. In addition, research could be conducted into how real-time data can be included and how the calculated impacts of the earthquake can be evaluated with help of field trials. Finally, the continued development of the tool into a usable app presents a great opportunity with usability design being a key point.

In conclusion, this highlights the relevance of user-oriented EENTs at the intersection of evacuation modelling and human behavioural research. While EENTs cannot completely replace human judgement, they can contribute to better-informed and calmer evacuations, thereby helping to mitigate the consequences of disasters.

7 Bibliography

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Appendix

The appendix contains the entire survey, divided into three parts. It was conducted in both German and English, with the English version being provided in the appendix. Please note the following symbolism:

- () indicates that only one answer can be selected.
- [] indicates that multiple answers can be selected.
- _____ indicates free-text answers.

Part 1

Thank you very much for participating in this survey! The survey takes approximately 10 minutes and is part of the master's thesis "Generation of Dynamic Earthquake Evacuation Maps" at the Department of Geography at the University of Zurich. This master's thesis involves the development of a prototype for an earthquake evacuation app. The app uses a routing function, similar to Google Maps, to show the fastest route to an evacuation site. The aim of this survey is to evaluate the functionality and results of this prototype and to find out whether the app can help people make better decisions in an evacuation situation. Your answers will be evaluated anonymously and used only for scientific purposes.

The survey consists of three parts:

The first part consists of general question about you and introductory questions about earthquakes and smartphone behaviour. The second part focuses on three earthquake scenarios. The last part consists of questions about the developed app.

1. What is your gender?

- () Female
- () Male
- () Other

2. Please enter your date of birth.

_____ (restriction to answer in date format)

3. Please enter the country you are living in.

- () Switzerland

- Germany
- Austria
- Other: _____

If “Switzerland” was chosen, question 3.1. appeared, otherwise it did not.

3.1. Please enter the ZIP code of your current place of residence

_____ (restriction to only allow numbers as answer)

4. Which type of area best describes your current place of residence?

- City
- Agglomeration/Suburban area
- Rural

5. What is your highest level of education?

- Primary School
- Secondary School
- Vocational training/apprenticeship
- Matura
- Bachelor
- Master
- Doctor/PHD
- Other: _____

6. On a scale from 1 to 5, how would you rate your local knowledge of the city of Zurich?

1 = Not at all | 2 = Little | 3 = Fair | 4 = Good | 5 = Very good

- 1
- 2
- 3
- 4
- 5

7. On a scale from 1 to 5, how would you rate your knowledge about earthquakes?

1 = Not at all | 2 = Little | 3 = Fair | 4 = Good | 5 = Very good

- () 1
- () 2
- () 3
- () 4
- () 5

8. How would you react if you were at home and a strong earthquake suddenly occurred?

9. How would you react immediately after an earthquake if many houses around you had collapsed?

10. Please indicate how much you agree with the following statements based on your smartphone usage.

10.1. "I use my smartphone daily for a variety of apps."

- () Strongly disagree
- () Disagree
- () Neutral
- () Agree
- () Strongly agree

10.2. "I find it easy to install and set up new apps."

- () Strongly disagree
- () Disagree
- () Neutral
- () Agree
- () Strongly agree

10.3. "I allow apps to access my location or send push notifications when needed."

- () Strongly disagree
- () Disagree
- () Neutral

- Agree
 Strongly agree

11. Which of the following warning apps do you use?

- MeteoSwiss
 Alertswiss
 Wetter-Alarm
 None
 Other: _____

Part 2

As part of this master's thesis, a prototype app was developed that calculates evacuation routes in the city of Zurich. Similar to a navigation system (e.g. Google Maps), the app visualises the fastest route from the current location to a safe place after an earthquake. In Switzerland, green spaces and parks are considered evacuation sites. After a very strong earthquake, rapid evacuation is crucial, as aftershocks and collapsing buildings can pose a serious threat for hours afterwards. In addition, evacuation sites not only offer protection, but also make it easier for emergency services to find and assist those affected. The prototype can model evacuation routes for scenarios involving strong earthquakes with magnitudes of 5.5, 5.75 and 6. The routes are designed for evacuation on foot, as roads are often blocked by debris after such an earthquake and cars or public transport can no longer be used. Evacuation on foot is therefore considered the safest method.

The aim of the app is to guide affected people to a safe place as quickly and reliably as possible, thereby reducing the impact of such disasters on the population.

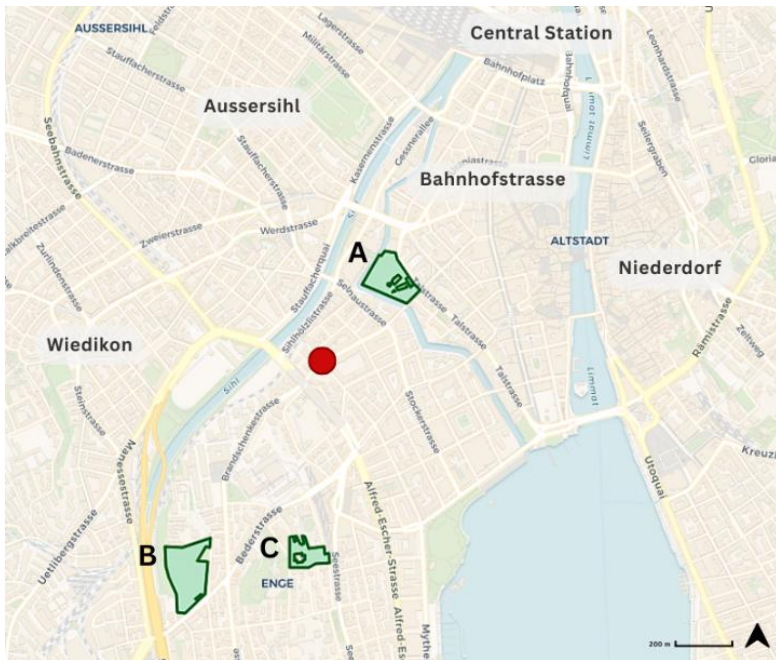
Below are four map sections from different areas of Zurich.

- The red dot marks your current location.
- The three highlighted parks represent possible evacuation locations.

Imagine you are in a scenario where a strong earthquake with a magnitude of 6 has just shaken the city and numerous buildings in your area have collapsed. It is 3 p.m. Now you must decide which of the three safe parks you would walk to as an evacuation site. Please indicate the letter of the park you have chosen and briefly explain your decision.

Note: You do not need to be very familiar with Zurich to complete this task. Make your decision based on the information shown on the map and your own judgment. Personal knowledge about Zurich is not required, however, if you are familiar with the city or the areas shown, you are welcome to include that knowledge.

Scenario 1: District 1



12. Please select from the three displayed options the park you would walk to as an evacuation site after a major earthquake.

- A
- B
- C

13. Please briefly explain why you chose this park.

14. On a scale from 1 to 5, how confident are you in your decision?

1 = Not confident at all | 2 = Slightly confident | 3 = Somewhat confident | 4 = Confident | 5 = Very confident

- 1
- 2
- 3

4

5

15. Would your decision change if it were 3:00 a.m. at night?

Yes

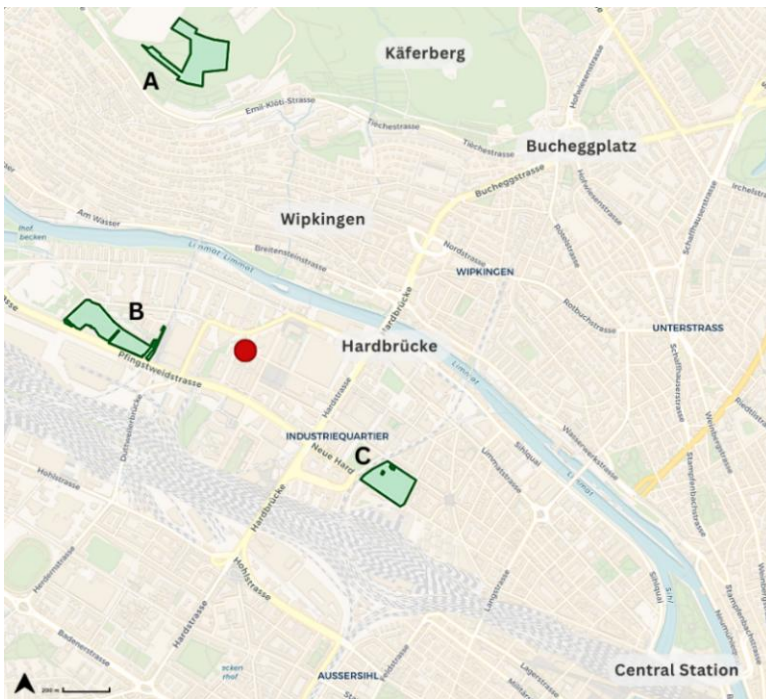
No

I am not sure.

If “Yes” was chosen, question 15.1. appeared, otherwise it did not.

15.1. Please briefly explain how your decision would change.

Scenario 2: Industriequartier



16. Please select from the three displayed options the park you would walk to as an evacuation site after a major earthquake.

A

B

C

17. Please briefly explain why you chose this park.

18. On a scale from 1 to 5, how confident are you in your decision?

1 = Not confident at all | 2 = Slightly confident | 3 = Somewhat confident | 4 = Confident |
5 = Very confident

1

2

3

4

5

19. Would your decision change if it were 3:00 a.m. at night?

Yes

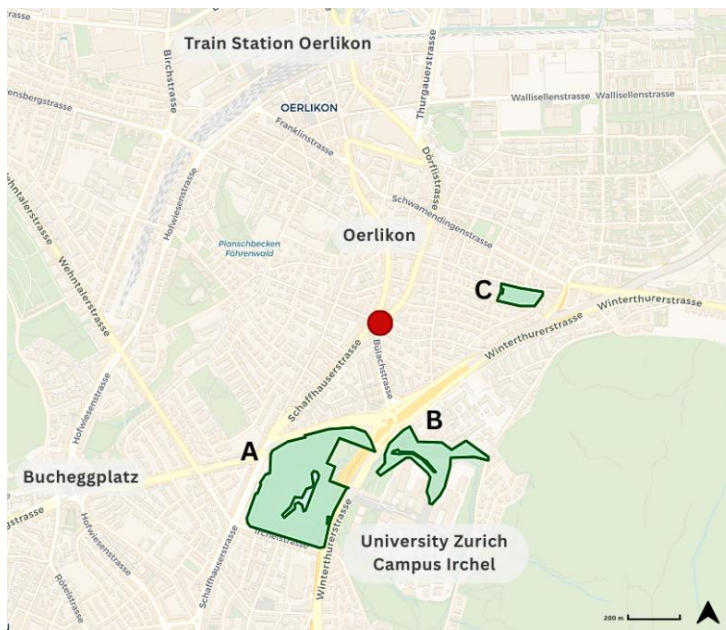
No

I am not sure.

If “Yes” was chosen, question 19.1. appeared, otherwise it did not.

19.1. Please briefly explain how your decision would change.

Scenario 3: Oerlikon



20. Please select from the three displayed options the park you would walk to as an evacuation site after a major earthquake.

- A
- B
- C

21. Please briefly explain why you chose this park.

22. On a scale from 1 to 5, how confident are you in your decision?

*1 = Not confident at all | 2 = Slightly confident | 3 = Somewhat confident | 4 = Confident |
5 = Very confident*

- 1
- 2
- 3
- 4
- 5

23. Would your decision change if it were 3:00 a.m. at night?

- Yes
- No
- I am not sure.

If “Yes” was chosen, question 23.1. appeared, otherwise it did not.

23.1. Please briefly explain how your decision would change.

Part 3

For the four map sections where you previously had to decide on an evacuation site, the app developed as part of this master’s thesis calculated the fastest possible evacuation routes. Below, you can see the identified routes together with the key factors that most influenced their course.

Scenario 1: District 1

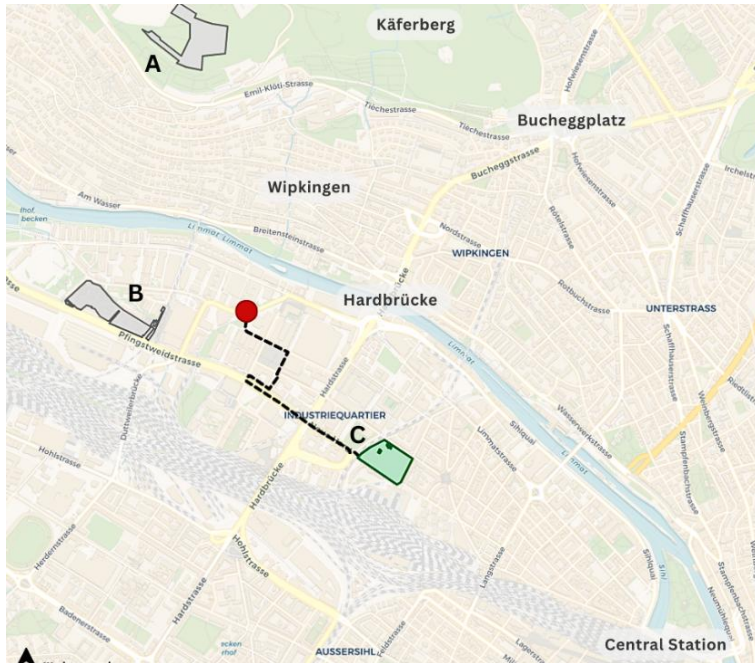
The app identified Park B as the fastest accessible evacuation park and visualized the corresponding route on the map.



After a strong earthquake, bridges should be avoided if possible, as they are at high risk of collapse. Therefore, Park A, which would only be accessible via a bridge, was not selected as an evacuation site. Instead, Park B was selected, as the route there is faster than the one to Park C. The reason for this is that fewer buildings would have been destroyed along the route to park B rather than the route to Park C, meaning that the roads are less obstructed. The probability of a building collapsing can be estimated based on its type of construction and year of construction.

Scenario 2: Industriequartier

The app identified Park C as the fastest accessible evacuation park and visualized the corresponding route on the map.



Park B was not selected as this region experiences strong soil amplification of seismic waves. This means that the earthquake is amplified due to soil properties such as soil material or material hardness. This causes several buildings to collapse and block the roads. Park A was excluded as well, as the route would pass over a bridge and the distance is too great. The app therefore selects Park C as the fastest evacuation location.

Scenario 3: Oerlikon

The app identified Park C as the fastest accessible evacuation park and visualized the corresponding route on the map.



Parks A and B are not selected as they are located in an area with a very high population density. The University of Zurich is in the immediate vicinity, which means that both the parks and the surrounding streets will be very crowded with students and staff. The app therefore decides on Park C.

The core principle of the evacuation app is not to calculate the shortest route, but the fastest one. Various factors are taken into account, such as the expected damage to buildings (calculated based on the age, construction type and volume of the building), population and traffic density, soil amplification of seismic waves (local amplification or attenuation of an earthquake), and the type of roads (e.g., bridges or tunnels). The app therefore seeks the quickest path to the nearest evacuation site by avoiding streets that are likely to be overcrowded or blocked by debris. These calculations are based on the personal location, the strength of the earthquake, the time of day, and several datasets from the city of Zurich.

A key factor is the difference between day and night: during the day, many people are at workplaces, schools, or universities, making certain areas densely populated. At night, however, most people are at home in residential areas. These variations in population density can result in different evacuation routes, as highly congested paths are avoided whenever possible.

With this knowledge about how the app determines evacuation routes, please answer the following questions regarding your assessment of the app and its functionality.

24. How important do you consider the following factors for the calculation of a safe evacuation route?

24.1. Collapse risk of buildings (e.g. collapsed buildings blocking roads)

- Not important at all
- Slightly important
- Moderately important
- Important
- Very important

24.2. Population density (e.g. densely populated regions can lead to overcrowded evacuation routes)

- Not important at all
- Slightly important
- Moderately important
- Important
- Very important

24.3. Traffic density (e.g. stationary cars as obstacles during an evacuation)

- Not important at all
- Slightly important
- Moderately important
- Important
- Very important

24.4. Soil amplification of seismic waves (local amplification or attenuation of an earthquake based on soil properties)

- Not important at all
- Slightly important
- Moderately important
- Important

Very important

24.5. Type of road (e.g. tunnels, bridges)

Not important at all

Slightly important

Moderately important

Important

Very important

24.6. Time of day (e.g., differences between day and night)

Not important at all

Slightly important

Moderately important

Important

Very important

25. When deciding on an evacuation site on the previous page, did you consider these factors?

25.1. Collapse risk of buildings (e.g. collapsed buildings blocking roads)

Yes

Partially

No

25.2. Population density (e.g. densely populated regions can lead to overcrowded evacuation routes)

Yes

Partially

No

25.3. Traffic density (e.g. stationary cars as obstacles during an evacuation)

Yes

Partially

No

25.4. Soil amplification of seismic waves (local amplification or attenuation of an earthquake based on soil properties)

- Yes
- Partially
- No

25.5. Type of road (e.g. tunnels, bridges)

- Yes
- Partially
- No

26. On a scale of 1 to 5, how helpful would this app be to you personally in a real evacuation situation?

1 = Not helpful at all | 2 = Slightly helpful | 3 = Moderately helpful | 4 = Helpful | 5 = Very helpful

- 1
- 2
- 3
- 4
- 5

27. On a scale from 1 to 5, how much do you trust the routes calculated by the app?

1 = Not at all | 2 = Slightly | 3 = Moderately | 4 = Strongly | 5 = Completely

- 1
- 2
- 3
- 4
- 5

28. On a scale of 1 to 5, how safe do you feel when you imagine using the app in an emergency situation?

1 = Not at all | 2 = Slightly | 3 = Moderately | 4 = Strongly | 5 = Completely

- 1
- 2

3

4

5

29. In an emergency, would you be more likely to follow the app or your own intuition?

I would follow the app

I would follow my own intuition

Both equally

30. Do you think that important factors are missing for the route calculation?

Yes

No

If “Yes” was chosen, question 30.1. appeared, otherwise it did not.

30.1. Which factors are missing?

31. Where do you see potential problems or weaknesses in the app?

32. Do you have any additional comments?

Please write down anything else that comes to your mind.

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Additionally, ChatGPT 5 was used as a supporting tool in the development of the EENT and in the analysis of the survey data, and Deepl was used to assist in the writing process of the thesis.

Signature: 