Assessing potential disruptions from earthquakes in the historical peninsula of Istanbul using 3D models

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Abstract

The increased number of city networks such as 100 Resilient Cities and Global Resilient City Networks, proves the importance of making cities disaster resilient. The major difficulty in this trajectory is the interrelated components in urban systems that influence each other and increase uncertainty in the risk assessment and management. Two-dimensional representations (e.g. maps and plans) do not take the effects of such a dynamic environment into account sufficiently. As a result, potential disruptions in a city caused by disasters in combination with the complexity of an urban system can be overlooked. Thus, static solutions are provided for a dynamic and complex environment. Istanbul is such an urban system that is in need of risk mitigation, as it is at increased risk to earthquakes and the cascading effects.

This study analyses the potential disruptions that impact traffic control with the help of a multi-hazard risk assessment for the historical peninsula of Istanbul. 3D modelling is introduced for the visualisation of disaster risk to support the communication of the causes of such potential disruptions. The additive normalization indicator-based approach is used to assess the socioeconomic, road and systemic vulnerability and risk. Besides, the EMS-98 Macroseismic method is applied to determine the building vulnerability and damage grades. The results show that the socioeconomic vulnerability is high to very high which is likely to contribute to traffic congestions and communication issues between the disaster coordinating bodies. Most buildings are expected to be 'very heavily damaged'. Consequently, while roads have low risk to damage, there is high risk for road blockages in the narrow streets of the case study area. These are areas where systemic risk is increased and accessibility for emergency services likely becomes obstructed. The application of 3D models improves the recognition of buildings and the identification of the causes of road blockages.

Keywords: Earthquake, Vulnerability, Risk, Potential disruptions, 3D models

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1 Introduction

1.1 Background

Disasters continue disrupting everyday life, causing economic loss, infrastructural damages and injuries or loss of human life. They create immediate humanitarian crises and negatively affect the socio-economic development of cities in the long term (Sim et al., 2018). The increased number of city networks, e.g. 100 Resilient Cities, Global Resilient City Networks, etc., proves the importance of making cities disaster resilient. The major difficulty on this trajectory is the uncertainty due to the complexity of cities. Meaning that in cities there are many interrelated components such as built-up environment, people, organisations, technology and economy that influence each other. According to Hollnagel et al. (2006), the performance of a system depends on the environment and its physical and social components. Accidents can never be eliminated from such a system and risk always remains (Perrow, 1984). Interactions between components aggravate the complexity and impact of disasters and make them hard to predict (Shimizu & Clark, 2015). Thus, failures and disasters are emergent phenomena.

Istanbul is one of these complex urban systems. It is the largest city in Turkey and among the largest cities in the world with an increasing population that is currently over 15 million inhabitants (World Population Review, n.d.). The city is located in the western part of Turkey and extended parallel to the North Anatolian Fault (NAF). The historical earthquakes on NAF resulted in injuries to people and even loss of lives in addition to great destruction of buildings and infrastructure (JICA & IMM, 2002). On the 7th of August, 1999, the Izmit earthquake resulted in over 17,000 deaths and damage estimated at 5 to 13 billion US dollars in Turkey (World Bank, 2018). A large number of collapsed or heavily-damaged buildings caused 500,000 people to be homeless (The Editors of Encyclopaedia Britannica, 2020). Overall, the total of 130 recorded earthquakes resulted in more than 80,000 deaths, more than 54,000 injuries and over 440,000 damaged houses (JICA & IMM, 2002). A worrying phenomenon that caught the eye of many researchers is the east to west progression of the epicentres of earthquakes along the NAF. This is illustrated in Figure 1. As a result, Istanbul is at increased risk of other major earthquakes (Atun & Menoni, 2014). Experts predict that a major earthquake with a magnitude larger than 7 will strike Istanbul in the next 30 years (35-70% chance) (Ergintav et al., 2014; Gunes, 2015; Johnson, 2020).

Figure 1: East to West progression of the Northern Anatolian Fault. Source: CGS Leeds (n.d., n.d.)

Next to the direct risk from earthquakes, Istanbul has shown to be at risk to the cascading effects of earthquakes, such as fire, liquefaction, landslides and underwater failures. Shaking from earthquakes can cause fires, especially in densely urbanised areas as there are more sources for ignition such as overturned heat sources and shorted electrical wiring. This can cause large conflagrations resulting in great destruction (Pampanin, 2021). The Izmit earthquake caused over 100 fire outbreaks in just Avcilar, Istanbul (JICA & IMM, 2002). Liquefaction can cause buildings to the tilt and collapse. It is known that liquefaction contributed to the collapsing of buildings during the Izmit earthquake in Turkey (Sabah, 2020). Regarding landslides, the entire area of Istanbul was classified as having a very low to low risk for landslides by JICA & IMM (2002); only a very small area in the Southwest of Istanbul has been classified as very high risk. That is why this cascading effect will not be considered in this study. Lastly, underwater failures result in tsunamis. The Marmara Sea, located to the south of Istanbul, is known to experience tsunamis, affecting the southern coastal areas of Istanbul. In the last 1600 years, Istanbul has felt at least 21 tsunamis of which almost half impacted its coasts. These historical events have shown that tsunamis hitting Istanbul can cause great damage and flood areas within the city (Alpar et al., 2003).

Although, Istanbul has developed multiple plans to reduce the disaster risk, the city remains vulnerable to earthquakes. The reason for this is rooted in national economic policy changes of the 1950s and 1980s. With the establishment of the republic, regional economic development became the main aim. However, in the 50s, Istanbul became the main focus for economic development attracting people and industries from the entire country. Consequently, there was an unexpected, massive increase in population. Between 1950 and 1990, the average population increased by 6.3% on average. Between 1937 and 1951, the urban planner Henri Prost prepared the first master plan to modernise Istanbul. He intended to introduce an integrated intra-city transportation network and establish industrial activities to boost the city's economy. However, he did not account for the large population increase of 860,558 in 1945 to 1,268,771 in 1955 due to the policy changes by providing sufficient infrastructure and housing, because when the master plan was being developed, the urbanization rate of Istanbul was slow. Besides this, to achieve the aim of the master plan, a large part of the old housing stock was being demolished to make place for public spaces, such as green areas and squares (Atun & Menoni, 2014; Tekeli, 1994).

As a result of the population growth and the scarcity of affordable housing, a housing problem emerged. Consequently, people started to construct houses illegally, creating informal settlements existing of weak structures, so-called 'gecekondu'. There was not enough governmental money to aid people in getting affordable housing. As a result, these vulnerable structures were legalised in 1967 and 1977 with the Squatter Amnesty Law. Besides this, only after Istanbul was classified as a first-level earthquake hazard zone in 1997, the building codes changed and became more restrictive. The 'gecekondu' and the buildings constructed before 1997 represent the largest component of vulnerable buildings in Istanbul (Atun & Menoni, 2014; Tekeli, 1994). In addition, the population growth resulted in a massive increase in motor traffic. Also, neglecting the sea and railway transportation increased the number of public transport vehicles. The public transit system was not able to account for these changes, resulting in traffic congestions which contributed to the current problems in Istanbul (Atun & Menoni, 2014; Tekeli, 1994). Overall, the city is very vulnerable to earthquakes and the cascading effects because of its high density, inadequate infrastructure and services, illegal building development and unbalanced socio-economic developed society. That is why it is necessary to make the city more earthquake-resilient to prevent further losses of human lives, injuries and damage to buildings (Atun & Menoni, 2014).

1.2 State of the Art

According to Harrison & Williams (2016), the concept of urban systems is novel in the field of urban resilience. However, a number of studies have been found on the impact of disasters on cities and on the complex interactions of interrelated components that contribute to this. Helbing et al. (2006) describe the causality networks of several disasters that contribute to their impact. Shimizu & Clark (2015) describes the effectiveness of existing national disaster management governance, policy and organisations against the short and long-term impacts of interconnected risks and cascading disasters, focussing on the Tohoku earthquake (Japan, 2011) and Hurricane Katrina (USA, 2005).

A significant number of studies have been done on the exposure of Istanbul to earthquakes (JICA & IMM, 2002), fires (JICA & IMM, 2002), floods (Alpar et al., 2003), tsunamis (Alpar et al., 2003), liquefaction (İnce et al., 2007; JICA & IMM, 2002) and landslides (İnce et al., 2007). Besides this, studies have been done on the vulnerability of buildings and people to these hazards, such as JICA & IMM (2002). Especially after the earthquake event of 1999, the number of studies accelerated as the need for earthquake preparedness and response planning was recognised (Erdik & Durukal, 2007).

However, the existing studies for Istanbul do not approach the earthquake problem in Istanbul from the angle of looking at the city as an urban system. They do not include the uncertain interactions and constantly changing environment when analysing the risk and developing the adaptation and mitigation plans. That is why the outcome of actions defined in a plan by regulations could be different than anticipated. Plans consider census data that is based on the residential population. Due to the changing number and ageing of residents and the differences between people during day and night, the plans could have a lower effectiveness than anticipated. The unpreparedness of people and institutions could influence their contribution to risk mitigation and their actions causing for example congestion of roads or staying in an unsafe building (Atun & Menoni, 2014).

1.3 Research problem

All of the studies that assess the vulnerability and risk to earthquakes and the cascading effects in Istanbul provide results in two dimensions. Two-dimensional representations do not take the effects of a changing environment with interrelated components in such an urban system into account sufficiently (Hollnagel et al., 2006). As a result, potential disruptions in the city caused by disasters can be overlooked and with that, the existing plans can become unapplicable to the real situation. Thus, the research problem is that static solutions are provided for a dynamic and complex environment. An example of a disruption is the blocking of roads by debris from collapsed buildings.

This study focuses on potential disruptions within traffic control. Traffic control refers to operational procedures that guide the evacuation of vehicles and access of emergency services to and from disastrous areas. This is very important to reduce the number of casualties. During disastrous events, the roads are important for emergency services, evacuation, transportation of relief goods, restoration activities and they prevent the spreading of fires (JICA & IMM, 2002). Thus, when roads are for example blocked by debris or traffic jams, important road functions and plans become inapplicable. Besides this, when an earthquake impacts the road functions, harbours are expected to perform various functions such as the storage and transportation of relief supplies, the transport of debris and providing shelter (JICA & IMM, 2002). Hence, it is important that these facilities remains functional in case of an earthquake. Therefore, it is essential to understand the causes of potential disruptions in the urban system. This way, measures can be taken that reduce the impact of earthquakes on traffic control in such a dynamic environment.

This study suggest to use 3D models for the visualisation of disaster risk to be able to better communicate the causes of potential disruptions. Using 3D models improves the effectiveness of communication in comparison to currently existing two-dimensional representations and the understanding on the environment and dynamism of an area, because they represent the environment better and with that, reduce the cognitive effort required to analyse the situation (Duzgun et al., 2011; Kemec et al., 2010; Redweik et al., 2017). As a result, 3D models can help to identify the causes of potential disruptions more easily. This provides the stakeholders with additional information about why and what problems can occur during an earthquake which could be useful when creating risk reduction plans, preparing evacuation plans, for first responses, and being more prepared in general. Thus, by using 3D models, environmental interactions should become more apparent which makes it possible to better understand the underlying causes of disruptions that impact traffic control and based on that suggest more dynamic solutions. Eventually, it might help in mitigating fatalities and injuries as plans become closer to reality.

1.4 Wickedness of the research problem

The difficulty in identifying the potential disruptions cause the stakeholders, such as the disaster coordinating bodies and emergency services, to have uncertainty within their decision-making processes and the development of mitigation and adaptation plans. This uncertainty is an aspect of so-called wickedness. A wicked problem has two dimensions: there is uncertainty in knowledge (technical and/or societal) that needs to be increased to understand a problem situation better, and there is a degree of consensus between the potential stakeholder groups involved. Thus, the lack of knowledge regarding the uncertain interactions in an environment and the impact this has on the timely decision-making of the stakeholders causes it to be a wicked research problem. 3D models can provide more realistic insights in the problems that can occur in an area during an earthquake event as described in the previous section. As such, this study aims to increase the understanding on the disruption that can occur and, with that, improve the decision-making of the related stakeholders. Consequently, it should reduce the wickedness of the problem.

1.5 Case Study Area: the historical peninsula

The focus of this study will be on the neighbourhoods surrounding one of the main hospitals of Istanbul, Çapa, located within the historical peninsula. These neighbourhoods include: Sehremini, Topkapi and Molla Gürani (Figure 3). This hospital is of great importance for medical aid after an earthquake event. However, the earthquakes could cause surrounding roads and ports to be lost, impacting the highly required traffic control.

The historical peninsula of Istanbul, also known as Fatih, is located on the seashore side in the South of central Istanbul. This area has great historical and cultural values and structures such as the Grand Bazaar, Hagia Sophia and Blue Mosque Square. It even is included in the UNESCO cultural heritage list. This causes it to be the centre of tourism in Istanbul, attracting tourist from all around the world. Around 98% of the tourists that come to Istanbul visit the historical peninsula. In addition, it is the heart of Istanbul's transportation, being the focal point for motorway, marine and railway systems. It is the home to some of the main ports in Istanbul and mass rapid transit terminals (Turgut, 2008).

However, the historical peninsula is known to face high-intensity earthquakes due to its distance to the fault line and its soft soil type which causes amplification (Bohnhoff, n.d.). Besides this, literature studies show that there is a considerable risk to the cascading effects of earthquakes. As the historical peninsula is densely urbanised (JICA & IMM, 2002), there is a risk to fires resulting from an earthquake (Turgut, 2008). Besides this, as it is located along the shores of the Marmara Sea, there is a considerable risk of liquefaction and tsunamis (Alpar et al., 2003; İnce et al., 2007). Due to the high concentration of risk in the historical peninsula, the area likely becomes isolated after a major earthquake (JICA & IMM, 2002). In addition, buildings might collapse and bury people beneath the heavy debris. This happened to the Grand Bazaar after the earthquake that hit Istanbul in 1894. A picture of the building after the event is shown in Figure 2. Lastly, the area is very vulnerable because it exists of low-quality dwellings which are being inhabited by low-income newcomers, high urban density, inadequate infrastructure and centrally located industrial activities (Atun & Menoni, 2014).

Figure 2: 1894 Istanbul Earthquake, Grand Bazaar. Source: Genç & Mazak (2001, p. 46)

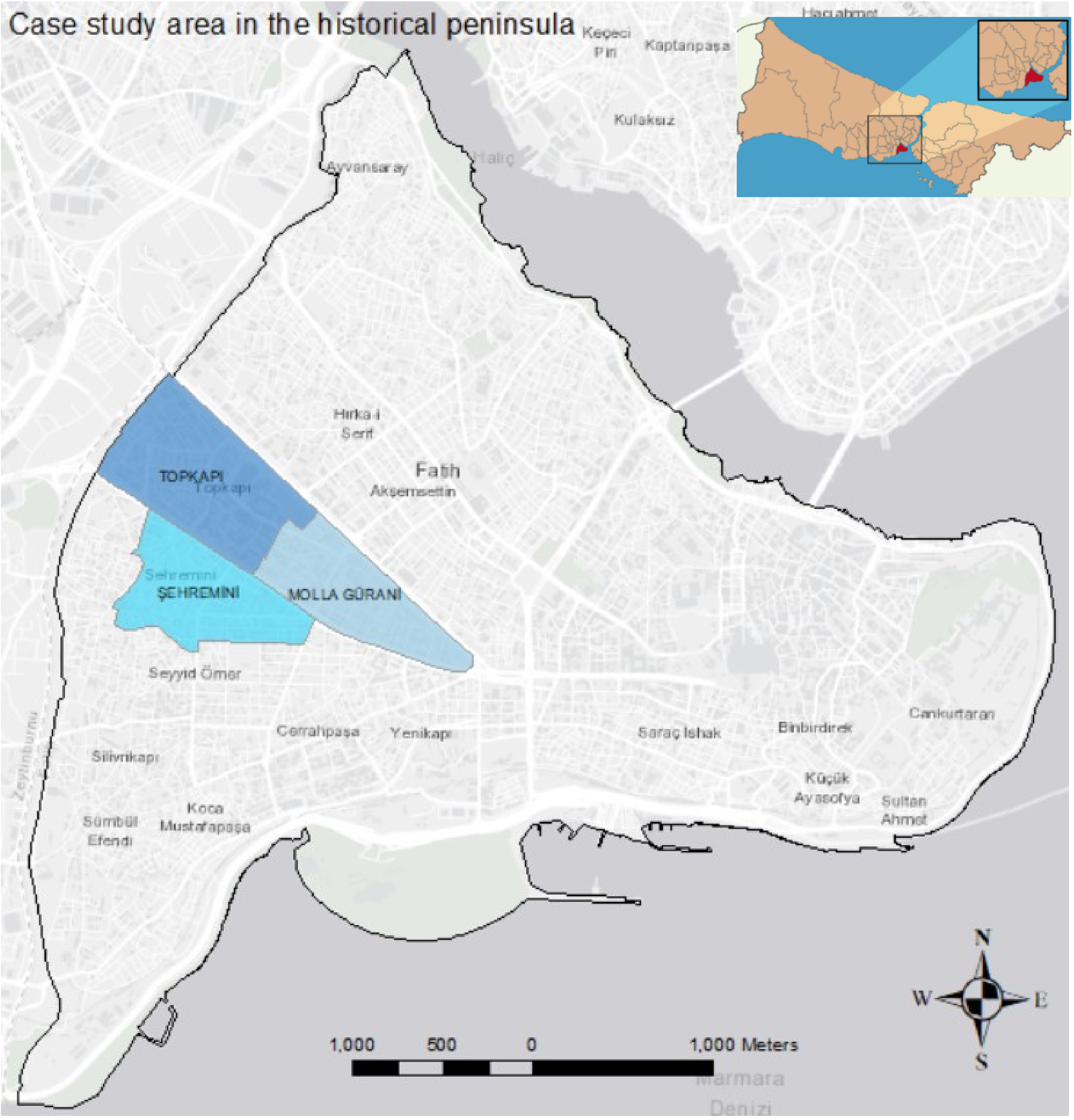


Figure 3: Map of Fatih, Istanbul in which the case study area is located. Sources: Author (2022) and https://en.wikipedia.org/wiki/Fatih (Istanbul overview map top right corner)

1.6 Research objectives and questions

The main objective of this study is: *To analyse the root causes of potential disruptions impacting traffic control in the neighbourhoods around hospitals to the risk from earthquakes and its cascading effects using 3D modelling.* This study will answer the following main research question: *What is the additional value of including the third dimension in disaster risk reduction?* This study will compare the result of the 3D modelling with the results of existing studies to identify the added value of including the third dimension to answer the main research question. For this study, five sub-objectives with one, two or three corresponding sub-research questions have been formulated. These are listed below:

Sub-objective 1: To investigate historical examples of how earthquakes affect complex cities in other parts of the world, i.e. the Tohoku, Christchurch and Kobe earthquakes.

1.1 What disruptions are caused by earthquakes in other metropolitan areas around the world that impact the traffic control?

1.2 What potential disruptions are applicable to the case study area?

Sub-objective 2: To do a vulnerability and risk assessment to earthquakes of the case study area.

2.1 What vulnerability indicators can be used?
2.2 What parts of the case study area are most vulnerable?
2.3 What parts of the case study area are more at risk?
2.4 Where can the identified potential disruptions occur?
2.5 How could these disruptions potentially impact the traffic control?

Sub-objective 3: To develop 3D models that visualise disaster risk and vulnerability of the case study area and use it to understand the reasons for potential disruptions impacting traffic control.

3.1 How to develop a 3D model for this purpose?
3.2 How does using the third dimension contribute to the understanding of the potential disruptions?

Sub-objective 4: To compare results from existing 2D analyses on potential disruptions in the historical peninsula with the results of the 3D model analysis.

4.1 What potential disruptions in the case study area have already been identified in 2D analyses?
4.2 Where do these potential disruptions occur within the case study area?
4.3 How do the identified potential disruptions differ from the results of the 3D model?

Sub-objective 5: To suggest measures that mitigate the risk from potential disruptions in the study area in the historical peninsula.

5.1 What structural interventions can be introduced in the historical peninsula to reduce the disaster risk?
5.2 What non-structural measures can be introduced in the historical peninsula to reduce the disaster risk?

1.7 Stakeholders

The stakeholders which could benefit from this study are the ones who are affected by earthquakes and the related effects, that is the general public in the case study area, and the ones who deal with disaster management and traffic control. The latter includes the emergency services and NGOs in addition to a variety of governmental bodies existing within the central government represented by the Disaster and Emergency Management Presidency (AFAD), the provincial government represented by the Metropolitan Municipality Disaster Coordination Centre (AKOM), the Istanbul Metropolitan Municipality (IMM) and district and municipal governments, the Fatih municipality in this case (JICA & IMM, 2002). By improving the understanding and communication of the earthquake risk and underlying causes of potential disruptions in the area, the disaster management and coordinating bodies can take more informed risk reduction measures which will be based on more realistic expectations for an earthquake event. This aids in making the general public more resilient to disasters. The related organisations that were contacted during this study and are thought to be the main stakeholders related to this study are provided in Table 1.

Table 1: Overview on the related stakeholders in this study. Source: Author (2022)

Stakeholder	Short description
General public	This refers to the residents and workers within the case study area.
Emergency services	This include the hospitals, police and fire brigade which are the first responders during an earthquake.
Disaster and Emergency Management Presidency (AFAD)	The leading governmental body that focusses on emergency management and civil protection against disasters in Turkey. This organisation does pre-, during-, and post-disaster work, such as preparedness, risk mitigation, emergency response, and recovery. It is the representative of the central government for the disaster management scheme (AFAD, n.d.).
Istanbul Metropolitan Municipality (IMM)	The governmental body that manages the city Istanbul. It focusses on making Istanbul sustainable, self-sufficient and green to improve the living conditions of the citizen by implement projects and making decisions about the municipal services. Also, it has a variety of bodies including research groups that focus on earthquakes (Istanbul Metropolitan Municipality, n.d.).
Metropolitan Municipality Disaster Coordination Centre (AKOM)	As a body of the IMM, this municipal organisation is the coordination centre for disasters and emergencies within Istanbul. From here, tasks among the organisation within the IMM are coordinated. Among others, the emergency services such as the fire brigade, the transportation departments and utility departments are part of this (Edwards et al., 2015; JICA & IMM, 2002).
Fatih municipality	A local municipality like the Fatih municipality is responsible for the management of their respective municipalities which include among others urban planning, the implementation of other projects and the management of the municipal services (JICA & IMM, 2002).
Non-Governmental Organisations (NGOs)	Related NGOs provide support for disaster management before and after disasters with resources, coordination and cooperation activities (Okay, 2005).
Research organisations	This include organisations which do research on earthquakes and risk mitigation in Istanbul in order to support decision-making and planning, such as the Istanbul Planning Agency (IPA), the Kandilli observatory and universities (Edwards et al., 2015).

2 Literature review

This chapter provides an overview of the literature review which has been done. Section 2.1 presents examples on how earthquakes have impacted the traffic control in areas around the world. Section 2.2 describes the methods used in literature to determine the vulnerability and risk in an area. Section 2.3 describes the methods that exists for 3D modelling. Both these sections are used for the decision of the methods as applied in this study.

2.1 Examples of earthquakes impacting traffic control around the world

Around the world, several metropolitan areas are prone to earthquakes and cascading effects. That is why there are a significant number of studies available describing the impact of earthquakes on complex urban systems. Such events are analysed to increase the understanding of how different components within an urban system interact and how these result in disruptions. This is used to identify potential disruptions that could occur in the case study area of this study. In this section, three different, historical earthquake events that happened around the globe and significantly impacted the communities are introduced. These events include the Tohoku earthquake that happened in Japan in 2011, the Kobe earthquake that also happened in Japan in 1995 and the Christchurch earthquake that happened in New Zealand in 2011. For each of them, the impact of disruptions on traffic control are highlighted.

2.1.1 Tohoku earthquake 2011

In 2011, an earthquake of magnitude 9.0 that happened off the coast of Tohoku struck the main island of Japan, which caused widespread damage on land. Besides this, it initiated a series of large tsunami waves that impacted the coasts of the country, causing a major nuclear accident at the Fukushima power plant (Rafferty & Pletcher, 2021). The tsunami consisted of waves of up to 24 meters in height, which surged as much as 10 km inland, and devastated large parts of the coast of Japan. The nuclear accident caused the radiation levels to be 20 times higher than the normal 'background' radiation levels in Tokyo. In addition, the earthquake itself caused widespread building damage and fires, the collapse of the Funjinuma irrigation dam in Sukagawa, and emergencies declared at the Fukushima-1 and -2 nuclear power plants (Khazai et al., 2011). Focussing on traffic control, several geographic, demographic, and cultural factors contributed to the immediate emergency response after the Tohoku earthquake to be complicated. In the aftermath of the earthquake there was large scale devastation and widespread damage to transportation routes which isolated several areas and with that blocked the access routes for the emergency services and the transportation of goods to these parts. Contributing to this, the concerns about radiation leaks from the Fukushima-1 nuclear power plant prevented transportation to several areas as well. Human behaviour caused the loss of communications networks (Khazai et al., 2011) which disrupted information sharing between governments and the emergency services, delaying the rescue activities (Shimizu & Clark, 2015). On top of that, human behaviour contributed to the occurrence of traffic jams which caused both the evacuating public and emergency services to get stuck (Ranghieri & Ishiwatari, 2014).

Like stated before, it was difficult to get the people and supplies for rescue activities to the devastated areas due to the widespread destruction which blocked the access routes and the loss of public transportations. Large areas, including whole towns and cities, had been washed away or were covered by great piles of debris and mud. Even in areas which normally are not considered to be rural around the world such as the Sendai region in Japan, the relative isolation caused the transport of essentials (food, water, fuel, etc.), aid materials and rescue teams to be difficult. Contributing to this, were the rough weather and the loss of a major airport in Sendai city which reduced air operations (Rafferty & Pletcher, 2021), leaving only ground transportation able to reach the devastated zones. However, shortage of fuel at local gasoline stations, prevented the smooth delivery of goods, which led to food and water shortages in the devastated areas (Shimizu & Clark, 2015). Also, districts around Fukushima, which usually are very accessible due to their proximity to the Tokyo metropolitan region, were prevented from receiving materials and human resources due to the radiation leaks. Besides this, the shortage of healthcare resources increased in rural areas due to the destruction of hospitals, clinics and nursing homes, and the loss of healthcare staff. The patients of hospital sometimes had to be transferred to other places which was very difficult due to the isolation of hospitals and nursing homes in the suburbs of cities or small towns (Khazai et al., 2011). Based on this, it can be said that not only the damage caused by the earthquake, but also by its cascading effects (radiation, fires, etc.) greatly disrupted the traffic control making it difficult to reach the devastated areas. In addition, the lack of resources, gasoline and healthcare resources in this case, increased the impact of the earthquake on traffic control.

As mentioned, human behaviour also contributed to the difficulty of transporting people and goods by reducing communication and causing traffic jams. As soon as the earthquake occurred, huge numbers of people who were worried about the safety of their friends and relatives started using their mobile phones and it subsequently became impossible to make calls or send emails due to the surge of communication traffic. As a result, communications systems were not functioning normally and it therefore took a very long time to gather information (Uno, 2016). This loss severely impacted critical communications between national and local governments, and between governments and first responders who were working at the affected nuclear power sites or medical sites in the devastated areas. The disruption of communications led to confusion in critical information distribution, hampering the emergency coordination and, with that, causing delays in appropriate response to urgent situations (Shimizu & Clark, 2015).

Next to communication issues, human behaviour contributed to traffic congestions. Many people wanted to leave with their family members, or thought that the tsunami would catch up to them if they left on foot. Thus, over half of the people used their cars to evacuate, resulting in one-third of them to get stuck in traffic jams. These traffic jams also resulted in emergency operators to get stuck as well, preventing them from being able to reach the impacted areas (Ranghieri & Ishiwatari, 2014). Based on this, it can be said that the behaviour of people increased the impact of the earthquake by causing loss of communication and traffic jams which disrupted the traffic control for emergency responders, delaying or even preventing them from reaching the impacted areas.

2.1.2 Kobe earthquake 1995

In 1995, an earthquake of magnitude 7.2 impacted Kobe, a city in Japan. Due to the seismicity and resulting fires and liquefaction, great devastation was caused to buildings, roads, railways, the harbour and people (Esper & Tachibana, 1998). The traffic control was impacted by the loss of access routes to the impacted areas due to damage (Iida et al., 2000) and blockages by debris and other infrastructural elements (Helbing et al., 2006). Besides this, like in the previous section, human behaviour contributed to traffic congestion causing not only the general public, but also the emergency services to get stuck (Iida et al., 2000).

The cause for the widespread damage can be attributed to the unpreparedness of Kobe for an earthquake. This is mainly because in the history of the city no major earthquake had happened. That is why the construction standards addressed other hazards known in the area, such as typhoons, strong winds, and landslides, while the measures of protection against earthquakes had been overlooked. As a result, many buildings and roads were vulnerable to the earthquake. 60% of the traditional wooden houses were seriously damaged or collapsed during the earthquake (Atun, 2014), and the destruction of the city and the highways was indescribable (Helbing et al., 2006). Contributing to this, were organizational errors that caused failure of the automatic gas shut-down. Consequently, a manual shut-down was done only several hours after the earthquake. In the meantime, broken gas pipes in wooden houses between the skyscrapers already caused hundreds of fires with widespread damage as a result (Helbing et al., 2006).

The most severe disruptions occurred in the transportation systems (Atun, 2014). The earthquake caused two expressways and the three railways (JR West, Hankyu and Hanshin) to be damaged and become impassable, resulting in total confusion about the transportation between the cities of Osaka and Kobe. Under normal circumstances, 200,000 vehicles per 12 hours travel over National Routes 2 and 43 and the Kobe and Harbour routes of the Hanshin Expressway. The Kobe line of the Hanshin Expressway is an elevated highway running directly above National Route 43. A section of the highway collapsed during the earthquake, causing both roads to become unusable. When the damaged Harbour route was closed as well, Route 2, which usually deals with only 15% of the overall traffic volume, was left as the only route connecting Osaka and Kobe after the earthquake (Iida et al., 2000). Besides this, the three railway lines which were used daily by 650,000 passengers were closed completely, leaving Kobe's transportation system at less than 5% of its normal capacity (Iida et al., 2000). Thus, the city resembled an isolated island with limited accessibility from the outside (Atun, 2014). Narrow roads throughout the city also became inaccessible as there was a high percentage of road blockages due to debris from collapsed buildings (JICA & IMM, 2002). Similarly, power supply lines hanging over the remaining streets and other broken infrastructure such as water pipes seriously obstructed traffic, including the emergency services and transportation of aid resources as it made roads more difficult to access (Helbing et al., 2006). According to Helbing et al. (2006), fire fighters were not able to reach the fires due to the destroyed roads and the aforementioned blockages. Next to ground transportations, helicopters were used for emergency transportation, but the availability of airways, the air traffic control, and use of the helipad were problematic. Besides this, ocean transportation was affected by damage to the port facilities (Atun, 2014; JICA & IMM, 2002). Based on this, it can be said that the earthquake greatly disrupted the traffic control either directly by causing damage to the roads, or indirectly by blocking the roads with debris or other infrastructural elements. Besides this, the loss of the other transportation networks reduced the possibility for emergency and transportation activities.

As mentioned in the beginning of this section, human behaviour also contributed to the impact of the earthquake on traffic control. The mobility of the inhabitants became restricted and there were traffic jams caused by those who wanted to leave or enter the city and abandoned vehicles (JICA & IMM, 2002). This caused serious difficulty with travel, not only for evacuating public but also for the emergency vehicles (Iida et al., 2000). Emergency services such as medical care, search and rescue, and fire-fighting activities had been obstructed. Thus, like in Section 2.1.1, the behaviour of people contributed to the disruptions that occurred in traffic control.

2.1.3 Christchurch earthquake 2011

On February 22, 2011, an earthquake of magnitude 6.3 impacted Christchurch, New Zealand. It was an aftershock of the Darfield earthquake which happened on the 4th of September, 2010, with a magnitude of 7.1. Even though its magnitude was lower, the damage was significantly more because it originated closer to the city. Especially the Central Business District (CBD) of Christchurch was impacted. The earthquake initiated widespread liquefaction in the CBD and eastern part of the city and rock falls in Port Hills, the southern part of Christchurch (Mary et al., 2011). The traffic control was impacted by the extensive damage to the road networks in combination with road blockages due to rock falls obstructing the transportation of goods.

The liquefaction, which contributed most to the impact from the earthquake, caused extensive damage to the road networks. It resulted in ground deformations (e.g. settlements, lateral spreading and sand boils) and, in combination with burst pipes, a lot of silt, mud and water which flooded the roads (Giovinazzi et al., 2011; Koorey, 2018). Many roads became uneven and got damaged with cracks and sinkholes. Besides this, many facilities which are located on the ground of the roads (e.g. manholes) were lifted creating obstacles on the roads. Also, most bridges and tunnels had to be closed, because the bridges often were shifted in height relative to the connected roads, and both had to get checked for structural damage (Koorey, 2018). As a consequence, several roads, bridges and tunnels became unusable, causing major disruptions for traffic, including the emergency services, and for transportation services (Yonson et al., 2020).

Next to the direct damage to roads, blockages also occurred. The rock falls in the Port Hills caused several important roads to get closed, because they were being blocked or there was danger from unstable rocks. These important roads include Evans Pass which is an important connection for oversized or explosive goods between Lyttelton Port and the city, and Main Road which connects the south-eastern suburbs to the city (Giovinazzi et al., 2011). This likely added to the difficulty of transportation goods and people to the impacted areas.

Lastly, human behaviour contributed to the impact of the earthquake on the traffic control. The earthquake occurred during the day when many people were at work, at school or doing other activities outside their homes such as shopping (Mary et al., 2011). These people were most of the time evacuated from major buildings and sent home. In combination with the aforementioned impact on the road network and damaged traffic signals, this caused significant traffic congestions in many parts of the city (Koorey, 2018). After the earthquake happened, many temporary traffic management measures were implemented to manage the traffic control, including speed restrictions, adjusted traffic signals and adjusted routes for the busses. However, congestions remained a problem for months after the earthquake (Giovinazzi et al., 2011). One thing learned from the Christchurch earthquake was that cycling is a very resilient travel choice directly after an earthquake. Cyclist were able to ride past the traffic jams and move around the obstacles on the roads where cars could not do this (Koorey, 2018).

During the Christchurch earthquake event, it can be said that the damage to the roads and the blocking of the roads with debris and infrastructural elements greatly disrupted the traffic control. Not only the earthquake itself caused these disruptions. Also its cascading effects, liquefaction and rock falls, contributed massively to this. So, just like in Sections 2.1.1 and 2.1.2, it is apparent that cascading effects and the resulting direct damages and indirect blockages of roads are important contributing factors to the impact of earthquakes on traffic control. Besides this, another recurring factor that also contributed to the disruptions in Christchurch is the behaviour of people which show to contribute to both the occurrence of traffic jams and communication issues.

2.1.4 Expected disruptions in the case study area

Based on the examples as described in the previous sections and knowledge on the case study area as described in Section 1.5, several ways have been identified which are expected to disrupt the traffic control in the case study area. First of all, it is possible that earthquakes could cause damage to the roads and buildings within the case study area like happened in the historical examples, especially since there are many low-quality buildings located in the area. In addition, the area is known to be densely built, which makes it likely that the expected damage to the buildings and the resulting debris could cause the narrow passageways to be blocked. Thus, the earthquakes could have a direct and indirect effect on the usability of the roads which could prevent or delay the emergency services and evacuation operations.

Besides this, Fatih is considered the heart of transportation of Istanbul. As such, there is a lot of traffic present in the case study area. During an earthquake it is likely that the already large number of vehicles will contribute to the occurrence of traffic jams. The behaviour of people could aggravate this. As described in Section 1.5, the area is home to many low-income newcomers and tourists. Therefore, it can be expected that the preparedness to and awareness of earthquakes and the corresponding action plans are low. Besides this, there are a lot of businesses present in the case study area. People who work there are likely to evacuate or go home during an earthquake event like happened in the business district of Christchurch during the Christchurch earthquake in 2011 as described in the previous section. Thus, like happened in the historical examples, it is likely the people will stop their activities and start move (likely with cars) in order to get home or evacuate in a chaotic manner, which contributes the occurrence of traffic congestions. Besides this, since major hospitals are located in or near the area (e.g. the Çapa hospital), people will try to enter the area to reach these hospitals. In addition, the use of communication networks could peak extremely which can cause communication issues for the emergency responders and disaster management organisations like happened during the Tohoku earthquake in 2011. The potential for road damage, road blockage, communication issues and traffic congestions are the disruptions which will be the focus for this study.

2.2 Risk and vulnerability assessment methods

The latest definition of disaster risk by the UNISDR's in 2017 is: 'the potential loss of life, injury, destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity' (Schneiderbauer et al., 2017, p. 40). Disaster risk is not only about the probability and intensity of a hazard event, but also about what is exposed to the hazard and how vulnerable these exposed entities are. For example, a severe earthquake in an area with very few people has less consequences than a minor earthquake in a highly populated area. Similarly, an earthquake in an area known to be prone to earthquakes, where there are better risk perception and stricter design standards of buildings, is impacted less than an area which is unprepared for such an event. As such, according to the Sendai disaster risk definition, risk exists of three components (Schneiderbauer et al., 2017):

- Hazard: 'The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources' (IPCC, 2014, p. 5).
- Exposure: 'The presence of properties, people, environment, etc. that are threatened by the hazard' (IPCC, 2014, p. 5).
- Vulnerability: 'Encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (IPCC, 2014, p. 5).

The fourth component, coping capacity, which is the ability of a system to respond after an hazardous event to mitigate losses, is generally considered to be a part of vulnerability (Schneiderbauer et al., 2017). Consequently, risk results from the combination of hazard and vulnerability of the exposed elements at risk. It can be represented by Equation 1.

$$Risk = Hazard\ x\ Vulnerability\ x\ Exposure \qquad (1)$$

A risk assessment process determines the probability of loss by analysing the potential hazards while including the vulnerability of the people, properties, livelihoods and the corresponding environment (van Westen & Greiving, 2017). In the past decades, more information on the people, communities and areas at risk has been requested by researchers. As a response, vulnerability assessment were introduced to improve the understanding of underlying societal factors and root causes that cause people and infrastructure to be at risk (Sherbinin, 2014). This knowledge is used in risk assessment, prevention and reduction, and in the development and implementation of disaster preparedness and response measures (Schneiderbauer et al., 2017).

According to van Westen & Greiving (2017), there are four methods of risk assessment: Quantitative assessment, Event-Tree Analysis, Matrix approach and Indicator-based approach. A quantitative assessment using 'curves', the matrix approach and indicator-based approach can also be used for the vulnerability assessment (Schneiderbauer et al., 2017). The methods are discussed in the following sections.

2.2.1 Quantitative assessment

This method can be used if all the components of Equation 2 can be quantified for several hazard scenarios and exposed elements:

$$Risk = \sum_{All\ hazards} \left(\int_{P_T=0}^{P_T=1} \left(P_{THS} x \sum_{All\ EaR} \left(P_{SHS} x (A_{ERHS} x V_{ERHS}) \right) \right) \right) \qquad (2)$$

In this equation P_{THS} is the temporal probability (return period) of a hazard scenario (HS) with a certain intensity and frequency. P_{SHS} is the spatial probability of the hazard scenario at a certain location. A_{ERHS}

is the number of exposed elements for a certain hazard scenario. V_{ERHS} is the vulnerability of the elements-at-risk for a hazard scenario.

The exposure is analysed by intersecting maps of the elements-at-risk and the intensity hazard map for each scenario, using GIS operations. A vulnerability curve relates the intensity of the hazard (e.g. ground motion, water depth, etc.) to the degree of damage or loss of the elements-at-risk expressed between 0 and 1 to quantify the vulnerability (Schneiderbauer et al., 2017; van Westen & Greiving, 2017). These curves are derived from past events by correlating the observed hazard intensities with the observed damage, through computer modelling or through expert opinions. After this, the numbers of elements-at-risk are multiplied with their corresponding vulnerability value for all scenarios. This is then multiplied with the spatial probability of the hazard at the locations of the elements-at-risk. The results represent the losses which is plotted against the temporal probability of the hazard to get a risk curve (van Westen & Greiving, 2017). This approach is illustrated in Figure 4.

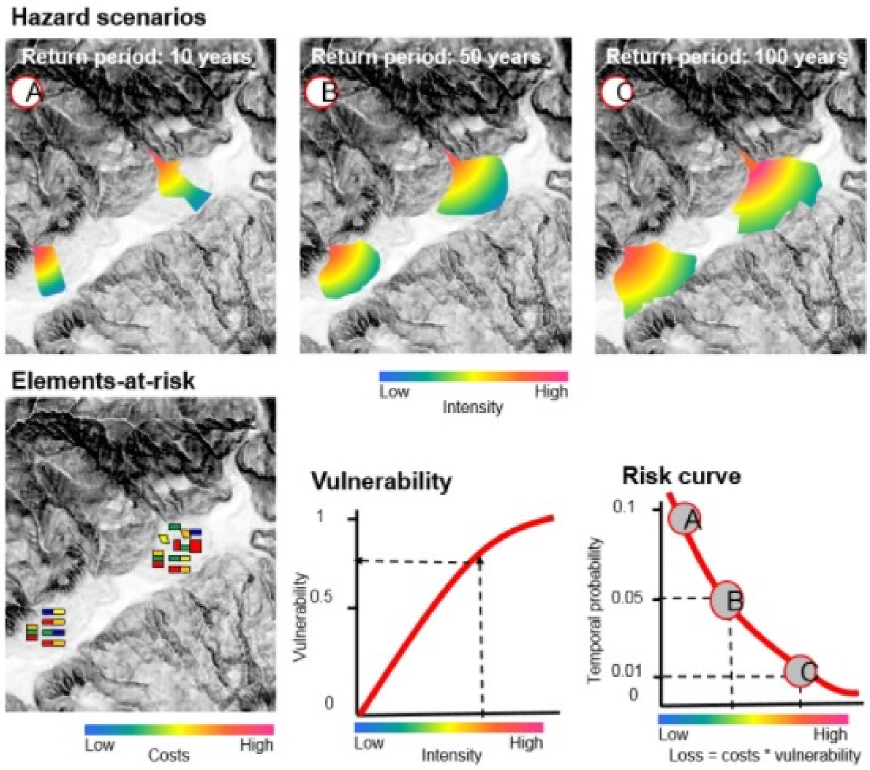


Figure 4: Schematic representation of the Quantitative Risk Assessment. Source: van Westen (2019, n.d.)

2.2.2 Event-Tree Analysis

In the event three analysis, the main focus is on the hazard. It is suitable for areas that are prone to multiple hazards. Some hazards can be cascading, meaning they occur in chains; so-called domino effects. The event-tree analysis is a system that analyses all possible combinations of hazards including the probability of the parameters in the system of interest. All the events are linked to each other by nodes. Each state of the system is considered at the nodes and characterised by a probability of occurrence (van Westen & Greiving, 2017). This approach is illustrated in Figure 5.

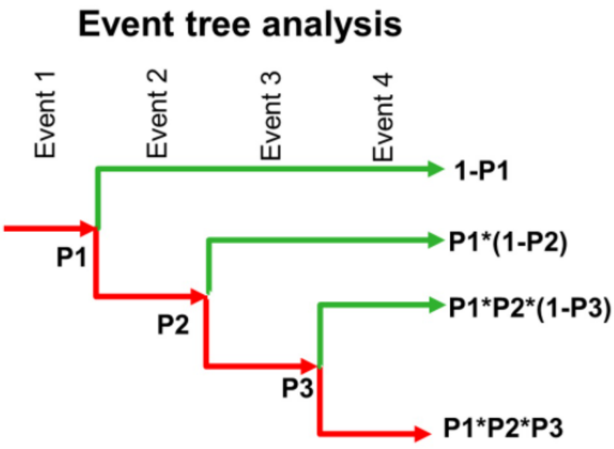


Figure 5: Schematic representation of the Event tree analysis. Source: van Westen (2019, n.d.)

2.2.3 Matrix approach

Risk assessments can often be complex and do not allow for an entirely numerical approach. The reason for this could be that many aspects of the hazard scenarios, elements-at-risk and vulnerability are difficult to define or quantify. Therefore, researchers often use the so-called risk matrices. These allow experts to classify the risk based on the limited available data. Thus, instead of using fixed values, there is more flexibility to include experts' opinions. In addition, it allows for the visualisation of the effects of the implementation of risk reduction measures. The use of this approach depends on the group of experts that are formed to identify the hazard scenarios, and filter and rank the hazards based on their frequency, impact and corresponding limits (van Westen & Greiving, 2017). The matrices have the frequency or probability of the hazard scenarios on one axis, and the impact on the other axis (Schneiderbauer et al., 2017). This approach is illustrated in Figure 6 below. Risk matrices are based on the combination of hazard and vulnerability information which can also be presented using matrices. Hazard matrices are used to classify hazards based on their frequency and intensity. Vulnerability matrices correlate the intensity of a hazard to the expected damage that results from such an event. Different matrices exists to be able compare and combine different vulnerabilities with varying units and corresponding impacts on the people, economy, environment and politics (Schneiderbauer et al., 2017).

		Impact			
		None	Small	Moderate	High
Frequency	Very High		High	Very High	Very High
	High		Moderate	High	Very High
	Moderate		Low	Moderate	High
	Low		Low	Low	Moderate
	None	No Risk			

Figure 6: Schematic representation of the Matrix approach. Source: van Westen (2019, n.d.)

2.2.4 Indicator-based approach

In many cases, (semi)-quantitative approaches are not appropriate, because there is insufficient data about the hazard and vulnerability available. Besides this, there are multiple components of vulnerability that one might want to include such as social and environmental vulnerability (van Westen & Greiving, 2017). Due to this multidimensionality of vulnerability, there is no single measure that is able to represent vulnerability on its own (Holand et al., 2011). In such case, the indicator-based approach is most suitable. In this approach, vulnerability and hazard are commonly described by a single index that has been constructed by the unitless aggregation of multiple quantified indicators (Abson et al., 2012; Reckien, 2018). These are measurable variables that each indicates an aspect of the vulnerability of communities to the hazard, and the hazard itself. The construction of indices can help to reduce the amount and complexity of the information that needs to be communicated, and to compare and rank results, because it indicates the interaction between multiple indicators through one 'score' (Abson et al., 2012; Reckien, 2018). In this approach, data for each of the indicators is collected at a certain spatial level, for example administrative units. The data of these indicators is standardized (reclassified between e.g. 0 and 1), weighted (or not), aggregated and then mapped to visualise the hazard, vulnerability and risk (van Westen & Greiving, 2017). This approach is illustrated in Figure 7. The resulting maps can help identify areas and societal groups who are most at risk to harm. This allows for more targeted policy measures and interventions that both mitigate current challenges and reduce future risks (Abson et al., 2012).

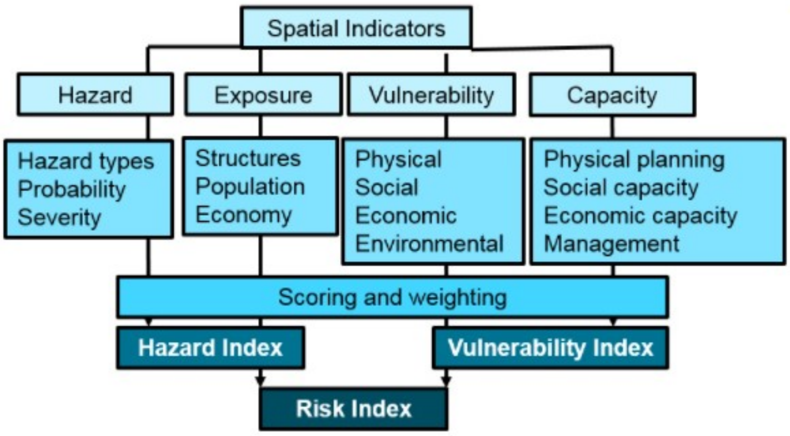


Figure 7: Schematic representation of the Indicator-based approach. Source: van Westen (2019, n.d.)

Based on the analysis of the historical earthquake events around the world that impacted traffic control as described in Section 2.1, it can be said that not only the physical vulnerability of buildings and roads, but also social vulnerability and systemic vulnerability contributed to the impact the earthquakes had on traffic control. The importance of including these different aspects of vulnerability is confirmed by Atun & Menoni (2014). The socioeconomic vulnerability is assessed to determine the mitigation capacity of the society. This includes social factors that influence the sensitivity of people to harm and their ability to respond (Cutter et al., 2003). The physical vulnerability is assessed to determine the exposure and fragility of the buildings and infrastructures. This can include characteristics of communities and the built environment, such as the level of urbanization, growth rates, and economic vitality, that contribute to the vulnerability of places (Cutter et al., 2003). The systemic vulnerability is included to evaluate the effects of interdependencies of components of an urban system on the accessibility and redundancy of such systems (Atun & Menoni, 2014). Thus, it is necessary to include multiple components of vulnerability in the risk and vulnerability assessments. That is why the indicator-based approach is best suited for this research.

There exist several methods to aggregate the different vulnerability indicators into an overall vulnerability index. The two main methods that are being used are: (1) the additive normalization approach which uses standardization such as z scores and (2) the variable reduction approach which uses data-reduction techniques such as the Principal Components Analysis (PCA), which is 'one of the most common multivariate factorial approaches' (Yoon, 2012, p. 826).

Additive normalization approach

For this approach, a limited number of vulnerability indicators are selected which are assumed to contribute to the vulnerability of the community or area of interest. This is based on knowledge from existing literature. In order to be able to aggregate the selected indicators, they first need to be standardized into a small, specified, unitless range to remove the unit of measurement (Reckien, 2018; Yoon, 2012). The reason for this is that the different indicators are often measured in different units. As distinguished by Yoon (2012), there are three commonly used standardization procedure:

- Z score normalization: this technique converts all indicators to a common scale with a mean of zero and a standard deviation of one, using the following equation: $Z = \frac{score-mean}{standard\ deviation}$
- Maximum value transformation: this technique rescales the values of the indicators between zero and one. It is defined as the ratio of the value of a variable (X_i) to the maximum value (X_{max}) for that variable. This technique uses the following equation: $R_i = \frac{X_i}{X_{max}}$
- Min-max rescaling techniques: this technique decomposes each variable into an identical range between zero and one. This is done using the following equation: $V_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}$

After standardization, the resulting values of the different indicators are aggregated, with or without weighing, to construct the overall vulnerability indices (Yoon, 2012). This is done using Equation 3 where w_i is the weight for each indicator and I_i is the value for each indicator. The weights that are applied in this study are discussed in Section 3.4.2.

$$VI = \sum_{i=1}^{n} w_i I_i \tag{3}$$

Variable reduction approach

The variable reduction approach has widely been used in human geography research. This approach uses an extensive number of the variables that influence the vulnerability of a community or area to create a vulnerability index. It differs from the additive normalization approach in that it includes a large number or potentially all possible indicators mentioned by literature to assess the vulnerability (Reckien, 2018; Yoon, 2012).

PCA is a statistical, data-reduction approach that transforms a large set of indicators into a smaller set existing of the most influential components (factors) based on variables that are highly correlated with each other. After this, the remaining components are normalized to make them unitless; and then mapped (Reckien, 2018; Yoon, 2012).

Literature shows that most researchers use the variable reduction techniques. According to Reckien (2018), this may be due to the easiness of data selection, as one can use all available data that is potentially related to vulnerability in the study area and does not need to care about their role, level of contribution, or correlation between single factors. According to Abson et al. (2012), such approach is used when it is assumed that correlating indicators are compatible and interchangeable and when the indicators strongly interact with each other or there are complex interaction which cannot be determined by simply summing and averaging the different indicators.

However, this approach is not favoured when it is known that some indicators influence the vulnerability significantly. As stated by Reckien (2018), PCA will most likely underestimate their importance as it treats indicators equally. Another disadvantage of this approach is the difficulty of interpretation of the results. As indicators are merged into components on the basis of correlation and not content-driven reasoning, the final vulnerability index is difficult to communicate to stakeholders. Lastly, this approach works best with an extensive set of input data which might cause the differences between population- or area-based input data to become less important.

The additive normalization approach is favourable when it is assumed that each vulnerability indicator adds a different element of vulnerability to the overall vulnerability index (Abson et al., 2012). The different indicators can be given different weights to account for their influence to vulnerability. However, most authors do not do this, because they lack an appropriate basis for weighting (Reckien, 2018). The disadvantage is that the underlying causes of vulnerability might get lost in the final vulnerability index, e.g. different locations may have the same vulnerability index due to different reasons. However, such problems can be overcome by including maps of the different vulnerability indicators. Besides this, including such maps is also necessary when using the PCA to show the causes of vulnerability. That is why researchers have questioned the credibility of the PCA model (Reckien, 2018).

Based on this, this study will use the additive normalization approach for the vulnerability assessment. The reasons for this are, that this research uses a limited number of input data, which is thought to be less functional when applying the data-reduction techniques. Besides this, the indicators are assumed to all contribute to a different element of the overall vulnerability of the case study area. Lastly, since the focus of this study is to improve the communication of risk to the stakeholders using 3D models, it is thought that the vulnerability assessment should also have results that are easy to communicate. As mentioned before, this is easier when using the additive normalization approach than the variable reduction approach.

2.3 3D modelling methods

A 3D city model is a representation of the urban environment where common urban objects, especially buildings, are represented with a three-dimensional geometry (Biljecki et al., 2015). There are various geospatial data acquisition methods, sensors and platforms which could be used for obtaining initial input data needed for 3D model generation. As distinguished by Billen et al. (2014), Kemec et al. (2010) and Kemec & Duzgun (2006), the different acquisition methods can be grouped into three: photogrammetric, active sensors and a combination of them together with GIS or CAD data (hybrid sensors). There are two main types of 3D modelling methods: topological modelling methods and geometric modelling methods. Topological modelling methods maintain the topological relations between the existing geometries and provides information about their surroundings. Geometric modelling methods use the actual geographic coordinates of objects (Ying et al., 2020).

2.3.1 Topological modelling methods

Topological modelling methods use a variety of data sources, e.g. images, LiDAR and 2D GIS data. The creation of 3D models is based on the existing topological relations of the 3D objects. This causes the data structure to be very consistent, because even if coordinates change, the relations remain the same. Besides this, it allows for complex spatial queries, operators and analyses (Li et al., 2016).

The most commonly method used for this is City Geography Markup Language (CityGML), approved by the Open Geospatial Consortium (OGC). It is an open data model used for data storage, sharing and exchange of geographical, topological and semantic information for 3D models (Agugiaro et al., 2018). CityGML defines ways to describe the geometry and attributes of 3D objects which can be found in urban areas, such as buildings, roads and bridges. These can be given textures or colours for their appearances. Besides this, relations between different 3D objects can be defined in CityGML (Ohori et al., 2018).

CityGML uses five levels of Detail (LoD) ranging from LoD0 to LoD4. LoD0 represent a 2.5D terrain model without any volumetric objects. In LoD1 buildings are represented as simple blocks. LoD2 adds roofs to the block model from LoD1. LoD3 is an architectural model which adds the additional exterior features of the buildings to the 3D models, such as the facades. LoD4 describes the interior structure of the buildings as well, such as the rooms and furniture (Kolbe, 2009; Ohori et al., 2018; Ying et al., 2020). An illustration of these LoDs can be found in Figure 8.

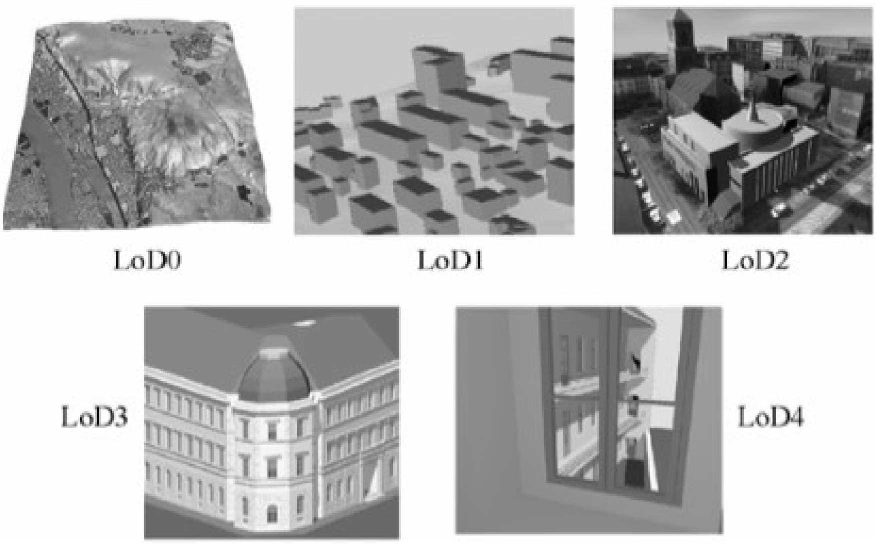


Figure 8: The different Levels of Detail as used in CityGML. Source: Kolbe (2009, p. 5)

According to Kolbe (2009), CityGML is very useful for the creation of 3D models. It can be used to create simple as well as complex objects, data can be very flexible as it can change based on their spatial and semantic structure and topological correctness throughout the modelling process, and it can be applied for specific domains using Application Domain Extensions (ADEs). However, topological methods are more complex than the geometrical modelling methods. The reason for this is that the topology should be defined correctly before the modelling starts. As stated by Li et al. (2016), especially on large, city-scale, this is known to be an issue. Besides this, CityGML needs professional knowledge about the use of the 3D Database Management System (DBMS) beforehand to organise the data well and avoid future data confusion.

2.3.2 Geometrical modelling methods

Ying et al. (2020) sub-divided geometrical modelling methods into several categories. The following have been found to be used to create 3D city models: image-based methods, point cloud-based methods and procedural methods.

Image-based methods

These methods are based on the image data collected with variety of sensors using photogrammetry and are used for the 3D modelling of buildings, as well as urban areas of different scales ranging from neighbourhood-scale to city-scale. Methods based on photogrammetry can use 2D terrestrial (Remondino & El-hakim, 2006) or aerial images (Toschi et al., 2017; Yalcin & Selcuk, 2015) to create the 3D models. Terrestrial images provide ground, vegetation and building facade details, but according to Billen et al. (2014) are difficult to be used on large scale, because there is limited area visible in each images and they all need to be calibrated and stitched together.

Yalcin & Selcuk (2015) and Toschi et al. (2017) both use the oblique photogrammetry method to construct 3D city models using aerial photogrammetry. According to them, 3D modelling using aerial images is one of the most common methods for 3D city modelling. Aerial images can provide accurate 3D information on the building footprints, the roof heights and structures and the terrain heights, and can be rectified into orthophotos that can be merged to cover large areas (Billen et al., 2014). The use of the oblique photogrammetry methods allows to extract information on facade textures.

By means of the different images, 3D models can be created through a mathematical model, with methods such as shape from shading or texture, and passive image-based methods which acquire 3D measurements from multiple views (Remondino & El-hakim, 2006). Image-based modelling can create accurate and realistic 3D models. However, it still requires a manual input and editing of the results, because automated methods are not applicable to real situations yet. In addition, the creation of detailed 3D models of complex objects, like historical city centres, remains difficult, because automated image-based modelling cannot capture the details of featureless surfaces without assumptions (Remondino & El-hakim, 2006; Toschi et al., 2017).

Point cloud-based methods

These methods are based on active sensors. High resolution 3D information is collected with Light Detection and Ranging (LiDAR) technology. Such technology measures the depth of objects by emitting lasers and measuring their reflectance. This results in an unstructured set of points, the so-called point clouds. Mancera-taboada et al. (2012) used LiDAR point clouds to create a 3D city model of Villalba, a town in Madrid. The method used in this study first classifies the points of the point clouds with an automatic process. The points can be classified using a variety of techniques such as simple discrimination (terrain or non-terrain) or more sophisticated discrimination (vegetation, buildings, etc.). How the points are classified can depend on certain parameters such as the elevation difference between neighbouring points and the pattern of the reflectance of the LiDAR points. After this, planes are extracted from the classified point clouds to create 3D models by applying reconstruction algorithms (Mancera-taboada et al., 2012).

According to Ying et al. (2020), the results of point-cloud based methods can provide 3D presentation with high-resolution and accuracy. However, automatic modelling using point clouds requires automatic structure segmentation and 3D reconstruction, which is very complex because of the occlusions between buildings or vegetation against buildings (Billen et al., 2014). According to Mancera-taboada et al. (2012) the use of LiDAR for 3D city modelling is only valid when a point density of more than 2 points/m^2 is used and it is being done by someone who can correct the errors that arise. Besides this, semi-automatic modelling using point clouds requires a lot of input from the operator, making it a slow process for large-scale areas (Billen et al., 2014). Thus, the creation of 3D models from point clouds is very compute-intensive. Even though, they provide a lot of semantic and geometric information, they are too ‘raw’ to be used for applications. That is why additional steps for classification and interpretation of the points are necessary (Rouhani et al., 2017).

Procedural methods

Procedural modelling uses a variety of data sources, e.g. images, LiDAR and 2D GIS data. This method extrudes 2D geoinformation that includes 3D attributes, such as heigh information, to create 3D objects. The automatic 3D modelling is based on Computer Generated Architecture (CGA) shape grammar which are rules that define the facades, roofs, windows, etc. in different Levels of Detail. There are several commonly used software that use this method to create 3D models, for example CityEngine (Ying et al., 2020).

Visualisation of the vulnerability and risk in an area using 3D modelling, as is the case in this study, has not been done extensively. The studies collected in literature which apply 3D modelling in this way, have been found to use procedural modelling. This could have a couple of reasons. First of all, according to Ying et al. (2020), the modelling operability of procedural modelling is very straightforward in comparison to CityGML and other methods. Besides this, according to Billen et al. (2014), procedural modelling is very flexible. Geometrical detail can structurally be added regardless of whether the modelling starts with or without an existing 3D base model, towards a highly detailed model. The trade-off is that with more details, the automation becomes less. However, for this research great detail in the 3D city model is not required. Lastly, it can easily be combined with GIS data to add geographical information to the model.

Catulo et al. (2018) applied a procedural modelling approach to create a 3D city model that visualises the seismic vulnerability of buildings. They stated that this method is very efficient at city scale and allows for an easy identification of vulnerable buildings and viewing of surrounding objects which helps interpreting the results.

Due to the ease of modelling operability, the possible combination with the commonly available GIS data and the potentially clear visual representation of the city and desired attributes, it is decided to use procedural modelling for this research. One of the studies that apply procedural modelling to visualise risk in an urban area is Redweik et al. (2017). They created 3D models of a case study area in Lisbon using the workflow as shown in Figure 9.

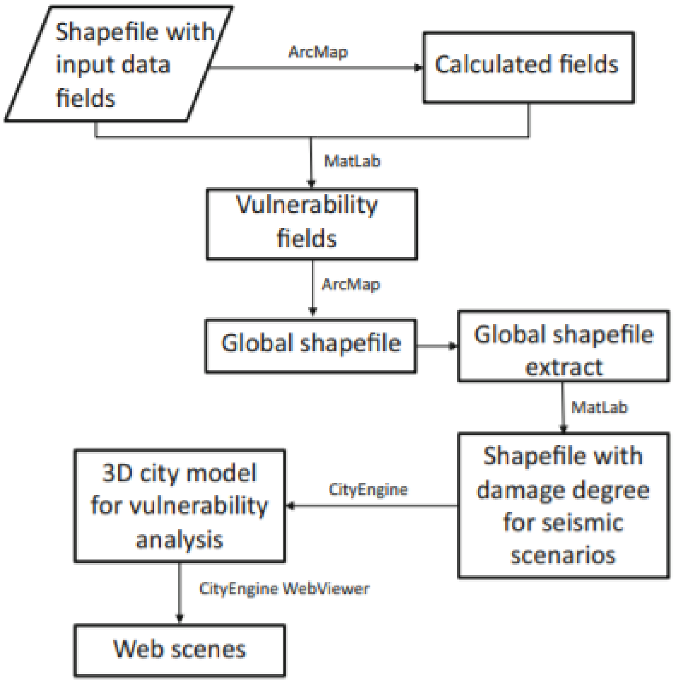


Figure 9: Workflow or 3D city modelling. Source: Redweik et al. (2017, p. 311)

Initially, a database is created in GIS which contains all the data of the buildings and their corresponding attributes, their calculated vulnerability indices, and the damage degrees calculated for two different macro seismic intensities for both a far and a near earthquake source. After this, the database is imported in the 3D modelling software CityEngine. Then, CGA rules are implemented to automatically build the 3D geometry of each building from the footprint and respective geometric attributes such as building height, and to provide each building with an appearance. Lastly, several layers are created depending on the demands of the stakeholders. A similar method will be applied to this research.

3 Methodology

This chapter provides an overview of the proposed research design of this study in Section 3.1. It describes the fieldwork that is done in Istanbul in Section 3.2. It show the input data that is used in this study in Section 3.3. It describes the applied methods used for the vulnerability and risk assessments and road closure analysis in Section 3.4. It described the applied method used for the procedural 3D modelling of the results in Section 3.5. Lastly, it presents how the results are evaluated in Section 3.6.

3.1 Proposed Research Design

Figure 10 presents the proposed research design as applied to this study. The input datasets are gathered through fieldwork and literature review. They are prepared using GIS to represent the vulnerability indicators and hazard models that are defined to be applicable to the earthquake risk in the case study area. The processed data is used for different vulnerability and risk assessments which is done with GIS as well. The results are imported into CityEngine for procedural 3D modelling. Eventually, based on the results of the vulnerability and risk assessment, the most vulnerable and the more at risk parts of the case study area can be identified using the statistics as determined with GIS. Besides this, the different potential disruptions that could impact the traffic control in the case study area as identified in Section 2.1.4 are assessed using the vulnerability and risk assessment and the created 3D models that represent the vulnerability and risk of the buildings and roads in the case study area. With this it is important to

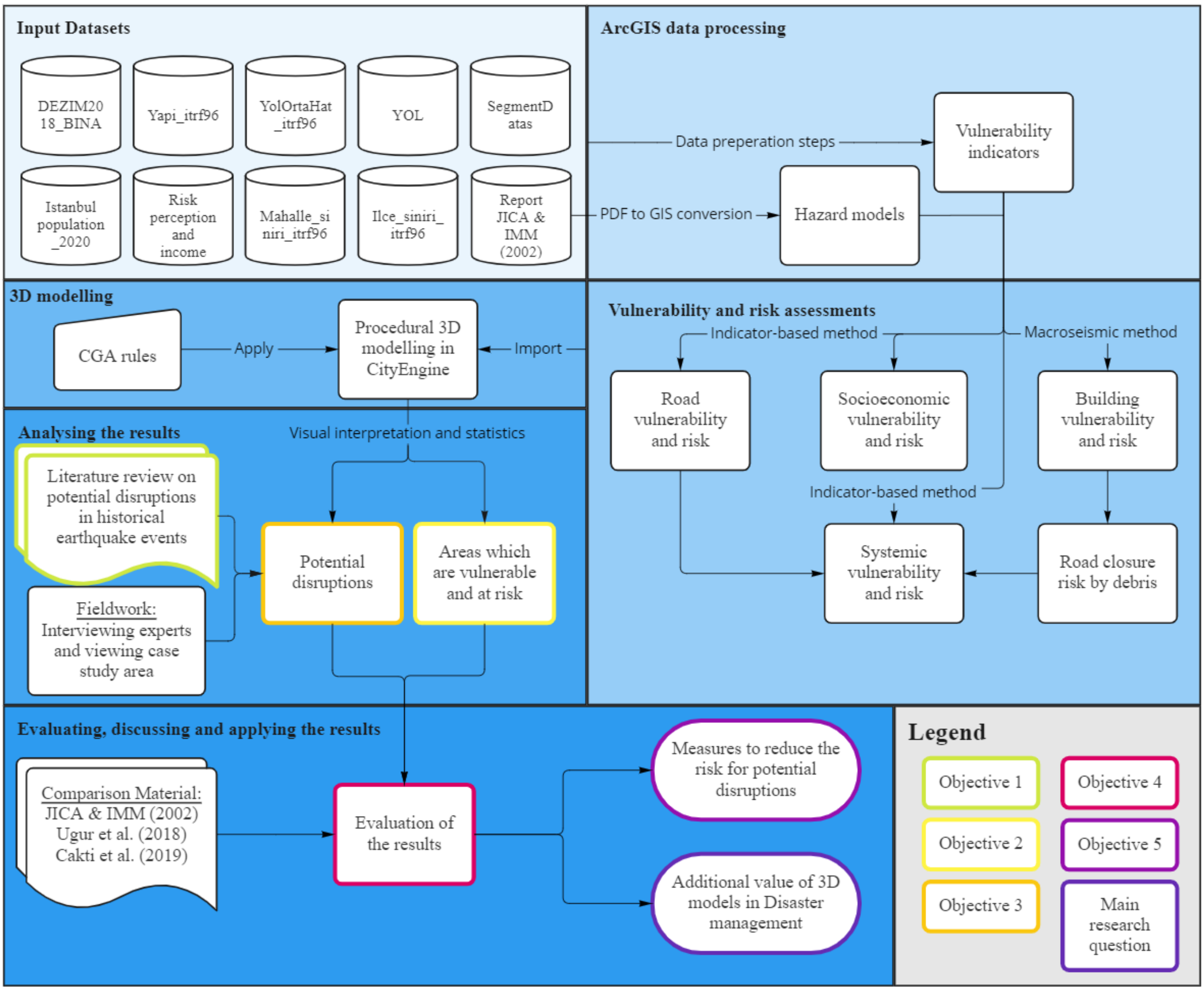


Figure 10: Proposed research design as applied in this study. Source: Author (2022)

think about interactions that happen within the case study area. These results are evaluated, discussed and used to suggest measures which reduce the risk for potential disruptions. How each applied method relates to answering the research questions and which sections contain the answers to the questions are presented in Table 2.

Table 2: Overview on the relation between the research questions, applied methods and results. Source: Author (2022)

Objectives	Research questions	Applied Methods	Research answers
1. To investigate historical examples of how earthquakes affect complex cities in other parts of the world, i.e. the Tohoku, Christchurch and Kobe earthquakes.	1.1	Literature review.	Section 2.1
2. To do a vulnerability and risk assessment to earthquakes of the case study area.	2.1	Literature review and fieldwork (Section 3.2).	Section 3.4.1
	2.2 2.3	Vulnerability and risk assessments using the additive normalisation indicator-based approach (Section 3.4.2) and EMS-98 Macroseismic method (Section 3.4.3).	Section 4.2
3. To develop 3D models that visualise disaster risk and vulnerability of the case study area and use it to understand the reasons for potential disruptions impacting traffic control.	3.1 3.2 3.3	Create 3D models through procedural 3D modelling (Section 3.5) and analyse these by visual interpretation in combination with the analysis of the results of objectives 1 and 2.	Section 4.2
4. To compare results from existing 2D analyses on potential disruptions in the historical peninsula with the results of the 3D model analysis.	4.1 4.2 4.3	Evaluation of the results using a comparison study of literature review (Section 3.6).	Section 5.1
5. To suggest measures that mitigate the risk from potential disruptions in the study area in the historical peninsula.	5.1 5.2	Visual interpretation of the results of objectives 2 and 3 in combination with the analysis of additional literature review.	Section 4.3
Main research question. What is the additional value of including the third dimension in disaster risk reduction?		Based on the comparison study of literature review (Section 3.6).	Section 5.1

3.2 Fieldwork in Istanbul

The fieldwork in Istanbul was from the 6th of December, 2021, till the 15th of December, 2021. In this time, two tasks were executed. The first one was meeting the relevant stakeholders as discussed in Section 1.7 to acquire knowledge about their responsibilities, the challenges which they expect to face during an earthquake, what plans they use during such times, and how they plan to improve the resilience of Fatih, and in particular the case study area, against earthquakes. This was done using semi-structured interviews which allowed for the interviews to be directed towards useful information for this study, while keeping opportunities open to explore other related topics relevant to the different stakeholders. At the start of each interview, this study was introduced shortly to provide the interviewees with some background information that could aid them to respond in ways related to the topic. After this, questions were asked targeting the information that could be collected from the different organisations. The structure of the interviews with a list of general questions is provided in Appendix A. The second task was about visiting the actual case study area to get a good feeling of the place and its local characteristics, and to make pictures and videos to be able to draw a good picture of the situation in the area.

The first interview was with the AFAD on the 7th of December. According to the spokesperson, there are 26 departments (such as the health care, transportation, shelter and communication departments) with each their own role in disaster management. The departments coordinate disaster responses, emergencies, etc. Eight of them are directly coordinated by the AFAD. The meeting was focussed on the challenges that the AFAD expects to face during an earthquake, especially in the case study area, what plans they use in such times and how they are working on mitigating these issues.

After this interview, one of the neighbourhoods of the case study area, Molla Gürani, was explored. Pictures that were taken during the exploration help in understanding the local characteristics of the neighbourhood. The most apparent characteristics were the narrow streets filled with parked cars and the old structures. The entire neighbourhood seemed to solely exists of buildings which are built before 1998 and therefore do not apply the currently existing building codes, but to those when Istanbul was classified as a second-level earthquake zone. Regarding their morphology, the buildings are mostly attached to each other, with few open spaces and somewhat varying heights. Besides this, the streets show to be approximately one car width wide, caused by the parked cars alongside the roads. In the pictures below (Figure 11), these characteristics can be identified.

Figure 11: Pictures of local characteristics of Molla Gürani in Fatih, Istanbul. Source: 1A-1C Author (December, 2021)

The second meeting was with the earthquake department of the Kandilli Observatory on the 8th of December. This department mainly has competence on the earthquakes themselves and their parameters, which is outside the scope of this study. The earthquake engineering department, which has competence on assessing the ground motion and the response from structures to mitigate seismic risk, was not available at the time. The contact person of the Kandilli observatory did share some documents describing earthquake models that could be useful for this thesis. Besides this, contact details were provided of a person from the Earthquake Engineering department who was willing to answer any questions and who was able to share a recording of the Tomorrow's Cities meeting. Tomorrow's Cities is an organisation which has the target to reduce the disaster risk for the poor in four different cities, including Istanbul.

On the 9th of December, the first interview was with the fire brigade. The fire brigade provided insightful information on how the local emergency services act during an earthquake, what tools they use and what challenges they face in their daily activities and which they expect to face during an earthquake. In addition, an app was showed which is used during the daily activities and an earthquake event. This app provides the fire brigade with information that allows them to coordinate their actions properly. The app can be seen in Figure 12.

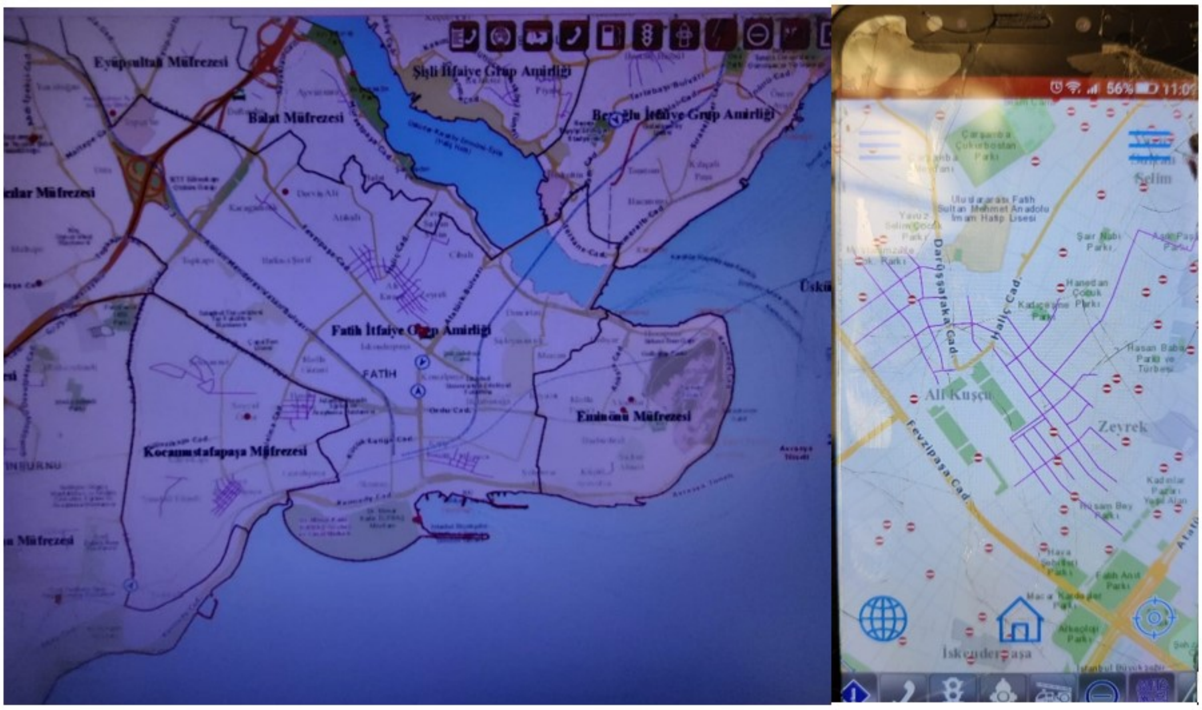


Figure 12: App used by the Fire brigade which helps them in their daily activities. Source: Author (December, 2021)

The next meeting was with the Dutch Consulate General in Istanbul. The target of this meeting was to gather contact information for people and organisations who could be of help for this research. Especially, the NOW fund was highlighted during the meeting, because through this organisation it could very easy to meet with other researchers and organisations related to the research topic.

On the 10th of December, first a meeting with AKOM was scheduled. AKOM is the main coordinating body during an emergency in Istanbul. According to the spokesperson, they are provided with information such as reports and data, and have their own sources of information, such as cameras and satellite data, to monitor the weather, earthquakes and their corresponding impacts (e.g. the impact of icy roads on the traffic). Within the organisation, a crisis centre is located where representatives of different managing bodies come together during a disastrous event to manage their respective teams. Like in the meeting with AFAD, this meeting provided information on how the AKOM functions during an earthquake, what challenges they expect to face, and how they mitigate these challenges.

Then, a meeting with the Istanbul Technical University was planned. This meeting focussed on the urban and social patterns of Istanbul and especially the patterns in case study area. It became clear how urbanisation and social behaviour contributed to the vulnerability of the area against earthquakes. Especially human behaviour turned out to be a big part of the expected challenges during an earthquake event. Besides this, from personal experience the spokesperson was able to describe an insightful ‘picture’ of the situation after an earthquake.

After this, the Fatih municipality was interviewed to get insights in risks that exists within the case study area and activities that are done to reduce that risk by the municipality that works specifically in and around the area of interest. The spokesperson explained what local characteristics in Fatih and specifically the case study area contribute to the vulnerability of the community. Besides this, the spokesperson described how municipality is working on making the area more resilient.

Lastly, the two main roads of the case study area neighbourhood Topkapi were explored. It became clear that the main local characteristics of this neighbourhood were the old buildings and narrow streets with parked cars. While the main roads are wide, where long traffic jams existed due to the jammed traffic flow at the intersections. As you can see below in Figure 13, the main roads all have traffic jams around the intersection. In addition, you can see similar old buildings and one car width narrow streets filled with cars as shown before.

Figure 13: Pictures of the local characteristics of Topkapi in Fatih, Istanbul. Source: 2A-2E Author (December, 2021)

On the 13th of December, an interview was set with the transportation department in the Istanbul Metropolitan Municipality (IMM). Their main aim is to manage the traffic flow in Istanbul. Managing this is done within the management centre of the organisation. Here they keep an eye on the traffic constantly and contact relevant companies if needed, for example a tow company to tow cars which are broken down on the roads. During an earthquake, the task of managing the traffic is shifted to the AKOM. In such moments, the IMM becomes ‘the eye’ for such disaster coordinating bodies, because the IMM can provide useful information using their own information sources. The meeting was about the work the transportation department does, what data and other sources of information they use (e.g. cameras, sensors and mobile vehicles), their expectations for challenges during an earthquake event and what plans are being executed in traffic control to reduce the disaster risk. In addition, they showed the programmes which they use to keep a clear overview on the traffic. Afterwards, data on the traffic intensity in Fatih was shared.

After this, was a meeting with the Istanbul Planning Agency. The IPA tries to identify different risks and their trends in Istanbul and focus on raising the awareness and preparedness of the public. Information was gathered on their expectations for challenges during an earthquake. Besides this, different sources for information and data were collected. This includes papers on vulnerability, hazard and risk in Istanbul. The provided data is on the education level of people in the case study area and answers to questions from a survey about the socioeconomic vulnerability in Istanbul which include risk perception as used in this study.

On the 14th of December, the neighbourhood Sehremini and some route segments of the neighbourhoods Molla Gürani and Topkapi were explored. Especially open spaces were explored to see whether they are really ‘open’. It became apparent that the entire area mainly exists of all similar buildings belonging to the old building stock. They look weak and deteriorated. Moreover, they usually are row houses which have slightly varying heights. This can result in damages during an earthquake as the buildings shake with different frequencies from each other. Also, like mentioned before, within each neighbourhood streets are very narrow with relatively tall buildings and usually parked cars alongside the roads. As a result, most roads can only allow one car width to pass. Besides this, again it became clear that roads, especially the main roads, are very prone to traffic congestions. The visited open spaces existed of parks and parking lots. These parks did usually show to be useful for assembly areas. However, they were not large. The parking lots were larger, but all of them were entirely filled with cars. So, most open space within them was occupied. These characteristics can be seen in the pictures below (Figure 14). Another important aspect of the Sehremini neighbourhood was the fact that the area hosts a market which covers a large area, causing many routes to get blocked. The walking route in the case study area for the entire fieldwork is shown in Figure 15.

3A 3B 3C

3D

3E

3F

3G

3H

3I

Figure 14: Pictures of the local characteristics of Sehremini and other case study area segments in Faith, Istanbul. Source: 3A-3I Author (December, 2021)

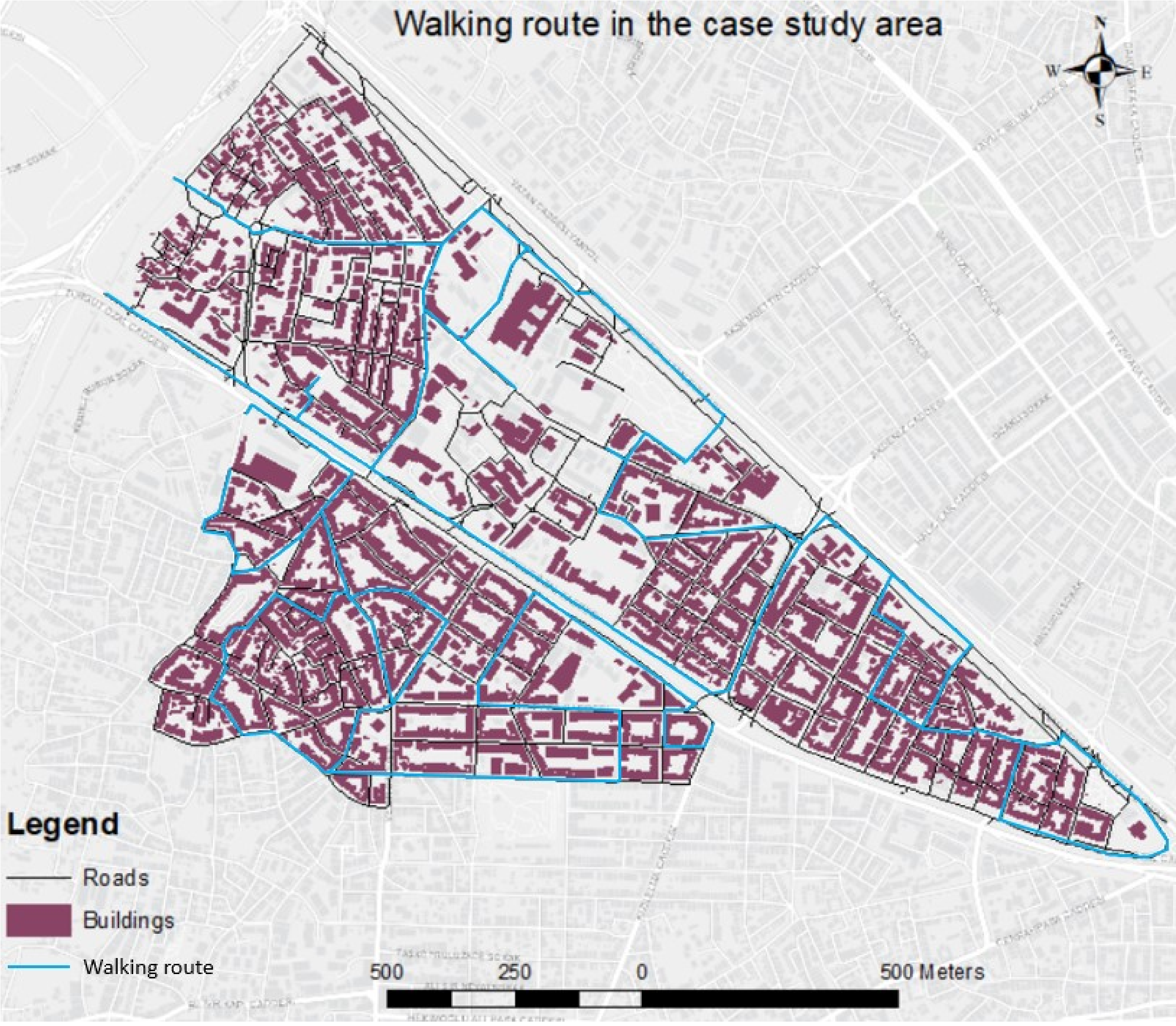


Figure 15: Walking route in the case study area during the fieldwork. Source: Author (December, 2021)

3.3 Input Data

Data used in this study had several sources. The two main sources of the data were the Istanbul Metropolitan Municipality (IMM) General Directorate of Mapping and the Istanbul Planning Agency (IPA). The IPA is an organisation that produces up-to-date and accurate data about Istanbul, develops social policies, designs the public areas of the city and works on realizing the vision of the city for 2050 to make Istanbul more liveable and sustainable. In addition, data was provided by the TKGM, the Land Registry and Cadastre of the Republic of Turkey. Next to this, data on the hazards in the case study area were obtained from the study of JICA & IMM (2002). This study proposed four different earthquake scenarios. Their model C is considered to be the worst-case scenario. That is why this study will use this model for the risk assessments. The model assumes a simultaneous break of the entire North Anatolian Fault with a magnitude of 7.7, the highest magnitude ever in the area causing peak ground accelerations of over 400 cm/s^2. Besides this, JICA & IMM (2002) provides the potential liquefaction zones and the potential for fire outbreaks in Istanbul based on model C. They show very high risk to liquefaction on the coasts of Fatih and low to low-moderate risk to fire outbreaks within Fatih. An overview of all the input datasets is provided in Table 3.

Table 3: Overview of the input data used in this study. Source: Author (2022)

Name	Description	Scale	Type	Date	Source
Yapi_itrf96	Building footprints within the case study area including corresponding attributes such as building typology and usage	Building-level	.shp	2013	IMM
YolOrtaHat_itrf96	Road network within the case study area including corresponding attributes such as width and type	Street-level	.shp	2013	IMM
Mahalle_siniri_itrf96	Administrative boundaries of the case study area	Neighbourhood-level	.shp	2013	IMM
Ilce_siniri_itrf96	Administrative boundaries of Fatih	District-level	.shp	2013	IMM
Istanbul population_2020	The male, female and total population, and the number of men and women with a certain education level per age group, in the case study area	Neighbourhood-level	.xlsx	2020	IPA
SegmentDatas	Average day-time (morning, noon, evening, night) vehicle velocity and traffic intensity per main road segment in Faith for 2021	Street-level	.shp	2021	IMM
DEZIM2018_BINA	Point data of the buildings including corresponding attributes such as construction year and number of stories	Building-level	.mdb	2018	IPA
Fatih_poi	Point data of different types of facilities (e.g. health facilities, fire brigades and police) within Fatih	Building-level	.shp	2015	TKGM
YOL	Road network within Fatih	Street-level	.shp	2015	TKGM
Risk perception and income level survey data	Survey data of the answers on questions about risk perception and income levels in Istanbul from Ugur et al. (2018)	Neighbourhood-level	.xlsx	2018	IPA
Earthquake peak ground acceleration	The peak ground acceleration of an earthquake based on the worst-case scenario from JICA & IMM (2002)	500x500m	.pdf	2002	(JICA & IMM, 2002)
Earthquake fire outbreak potential	The fire distribution caused by an earthquake based on the worst-case scenario from JICA & IMM (2002)	Neighbourhood-level	.pdf	2002	(JICA & IMM, 2002)
Earthquake liquefaction potential	The liquefaction caused by an earthquake based on the worst-case scenario from JICA & IMM (2002)	500x500m	.pdf	2002	(JICA & IMM, 2002)

3.4 Vulnerability and risk assessments

As stated in Section 2.2.4, for this study the additive normalisation indicator-based approach is used for the vulnerability and risk assessments. In this approach, vulnerability and hazard indicators are used to determine an vulnerability and risk indices. This study distinguishes between four categories in the vulnerability and risk assessments: the physical road vulnerability and risk, the physical building vulnerability and risk, the socioeconomic vulnerability and risk and the systemic vulnerability and risk. The physical vulnerability of buildings and roads, represents which of these are structurally weak (Banica et al., 2017) and therefore can result in disruptions. Social vulnerability indicators are used, representing characteristics of people and their situation that influence their ability to anticipate and resist the impact of disasters (Konukcu et al., 2015) which is thought to represent the behaviour of people. Systemic vulnerability is included, as this comprises the accessibility of emergency services to the disastrous areas and vice versa (Banica et al., 2017). Throughout the study, these different assessments will remain separated to be able to clearly distinguish between the types of vulnerability and risk that could cause a certain disruption.

3.4.1 Selection of indicators

An overview of the vulnerability indicators and hazard indicators which are considered applicable to the case study area is shown in Table 4. The vulnerability indicator 'critical infrastructure' is excluded in the assessments, because it has been found that no critical infrastructure is present in the case study based on the provided data and fieldwork. Besides the indicator 'building maintenance level' is excluded, because the information on this in the case study area is unknown. Section 4.1 provides a more elaborate description on how the indicators are prepared using the data shown in Table 3. It includes the steps that are taken in GIS, which assumptions are made and describes the workflow.

Table 4: Overview of the vulnerability and hazard indicators used in the vulnerability and risk assessments of this study. Source: Author (2022)

Indicator types	Vulnerability indicators	Description	Dataset(s)
Physical indicators	*Buildings*		
	Building typology	This includes the stiffness, strength and ductility capacity of buildings to forces that exert stresses, representing building strength. It strongly affects the behaviour of buildings during an earthquake. Consequently, identical buildings of which only the type of construction is different behave very different during an earthquake, e.g. brick and stone are more susceptible to seismic damage than reinforced concrete structures (Banica et al., 2017; Pavić et al., 2019).	Yapi_itrf96
	Maintenance level of buildings	Maintenance is necessary to ensure that all elements in buildings are in good state to perform its function (Singh et al., 2019). Lower maintenance levels, increase vulnerability.	Yapi_itrf96
	Building age	The age of buildings represents building strength, as over time they have been impacted by earthquakes potentially causing structural problems and age represents which building codes have been used (Atun & Menoni, 2014; Pavić et al., 2019). The older the building, the more vulnerable.	DEZIM2018_BINA
	Building height	The height of the building relates to the dynamics of the structure. Vibrations from earthquakes interact with these dynamics, resulting in damage (Banica et al., 2017; Pavić et al., 2019). This indicator is also used in Caliskan et al. (2006).	DEZIM2018_BINA
	Difference in building height with adjacent buildings	This difference in building height can result in a pounding effect between the buildings due to their different dynamic behaviour, resulting in more damage than expected (Grünthal & Schwarz, 1998; Malladi, 2012).	DEZIM2018_BINA and Yapi_itrf96
	Building position in building block	When buildings are attached to each other it is possible that irregularity in the stiffness of the buildings is caused which will lead to increased damage (Grünthal & Schwarz, 1998).	Yapi_itrf96
	Use of building	Depending on the use of buildings the vulnerability is affected. During the day or night the use determines how many people are inside. Besides this, the change in usage could affect the building strength as structural element might be removed. This indicator is used in Caliskan et al. (2006).	Yapi_itrf96
	Roads		
	Road width	According to El-Maissi et al. (2020) this is a commonly used indicator. Wide roads are most capable of securing emergency services. Thus, the wider the roads, the lower the vulnerability.	YolOrtaHat_itrf96
	Maintenance level of roads	According to El-Maissi et al. (2020) this is a commonly used indicator. The lower the maintenance level, the more deterioration or damages exists, increasing vulnerability.	YolOrtaHat_itrf96
	Road material	According to Tung (2004), material is one of the main factors which determine the strength of structures such as roads and bridges.	YolOrtaHat_itrf96

	Critical infrastructure	According to El-Maissi et al. (2020) critical infrastructure affect the vulnerability of the road system. Thus, (roads with) critical infrastructures are considered more vulnerable.	YolOrtaHat_itrf96
Socio-economic indicators	Population density	A high density of population can increase damages in case of a strong seismic event (Banica et al., 2017). The higher the density, the higher the vulnerability. Difference between day and night population contributes to vulnerability (Atun & Menoni, 2014).	Istanbul population_2020
	Percentage of people with low-education levels	Awareness of disasters increases with the level of education (Konukcu et al., 2015). A higher level of education, reduces the vulnerability.	Istanbul population_2020
	Percentage of people over 65 years old	The age of people determines their susceptibility to hazards. Due to their limited mobility and incapability for withstanding disasters, people of old age (older than 65) are less capable of getting out of harm's way and thus are more vulnerable than others (Cutter et al., 2003; Yüce & Arun, 2010).	Istanbul population_2020
	Percentage of people with low-Income levels	The economic status of a household is important for compensating for and coping with the losses and the other negative effects of a disaster (Cutter et al., 2003; Konukcu et al., 2015; Yüce & Arun, 2010). The lower the income, the higher the vulnerability.	Risk perception and income level survey data
	Risk Awareness	The ability of individuals to cope with hazardous events largely depends on this indicator (Atun & Menoni, 2014; Konukcu et al., 2015). The more aware, the lower the vulnerability.	Risk perception and income level survey data
	Risk Preparedness	The ability of individuals to cope with hazardous events largely depends on this indicator (Atun & Menoni, 2014; Konukcu et al., 2015). The more prepared, the lower the vulnerability.	Risk perception and income level survey data
Systemic indicators	Travel time to health facilities	Access to health services is very important for appropriate treatment and to eliminate injury immediately after a disaster (Banica et al., 2017; Konukcu et al., 2015). Thus, the closer the health facilities, the lower the vulnerability.	Closest facility network analysis using Fatih_poi and YOL
	Travel time to emergency services	Time for emergency services (e.g. the police and fire brigade) is highly important in order to get to damaged building and contribute to saving lives (Banica et al., 2017). Thus, the closer the emergency services, the lower the vulnerability.	Closest facility network analysis using facility point data Fatih_poi and YOL
	Solid to void ratio	Density of the built area could facilitate the occurrence of blockages in case of collapse (Banica et al., 2017). The higher the density, the higher the vulnerability.	Calculated using the building footprints of Yapi_itrf96
	Traffic intensity	Transportation is a big challenge in Istanbul. So, during an emergency, many roads will be blocked with cars (Atun & Menoni, 2014). Higher traffic intensity, increases vulnerability.	SegmentDatas

3.4.2 Applying the additive normalisation Indicator-based approach

Before combining the prepared vulnerability indicators to determine the vulnerability indices using the additive normalisation indicator-based approach as described in Section 2.2.4, they first need to be standardized. Table 5 provides an overview on how the different vulnerability indicators are standardized. Note that the indicators which determine the vulnerability of the buildings are not included. The reason for this is that the EMS-98 Macroseismic method is used to determine the building vulnerability for which no standardization is required. This method is a specially prepared indicator-based method which is used to determine the vulnerability and damage of buildings across Europe for specified earthquake events. A more elaborative description on this method is described in Section 3.4.3. Besides this, the liquefaction potential has not been standardized as well. The liquefaction model of JICA & IMM (2002) shows that there is no potential for liquefaction within the case study area.

However, the main roads on the coasts of Fatih are at risk of being affected by liquefaction. This is assumed to cause a change in traffic flow along roads near the liquefaction zones which could impact the accessibility of the case study area. The further away from the liquefaction zones, the lower the impact. That is why, this hazard is only included as the indicator 'proximity to the liquefaction zones' in the systemic risk assessment, not as a hazard for the other risk assessments.

Table 5: Standardization and weights of the indicators for the vulnerability and risk assessments. Source: Author (2022)

Vulnerability and hazard types	Indicators	Weight	Classification	Values
Road vulnerability	Road width	0.33	Very wide (>16m) Wide (13-16m) Moderate (9-12m) Narrow (5-8m) Very narrow (0-4m)	0.2 0.4 0.6 0.8 1
	Road maintenance level	0.33	Good Bad	0.25 0.75
	Road material	0.33	Paved Unpaved	0.25 0.75
Socioeconomic vulnerability	Population density	0.167	Maximum value transformation 0-0.25 0.25-0.5 0.5-0.75 0.75-1	 0.25 0.5 0.75 1
	Percentage of people with low-education levels	0.167	0-13% 13-22% 22-33% 33-80%	0.25 0.5 0.75 1
	Percentage of people with low-Income levels	0.167	0-5% 5-11% 11-27% 27-100%	0.25 0.5 0.75 1
	Percentage of people over 65 years old	0.167	0-8% 8-13% 13-20% 20-67%	0.25 0.5 0.75 1
	Risk Awareness	0.167	Very high High Medium Low	0.25 0.5 0.75 1
	Risk Preparedness	0.167	Very high High Medium Low	0.25 0.5 0.75 1
Systemic vulnerability	Travel time to health facilities	0.2	Maximum value transformation 0-0.25 0.25-0.5 0.5-0.75 0.75-1	 0.25 0.5 0.75 1
	Travel time to fire brigades	0.2	Maximum value transformation 0-0.25 0.25-0.5 0.5-0.75 0.75-1	 0.25 0.5 0.75 1

	Travel time to police	0.2	Maximum value transformation 0-0.25 0.25-0.5 0.5-0.75 0.75-1	 0.25 0.5 0.75 1
	Solid to void ratio	0.2	Maximum value transformation 0-0.25 0.25-0.5 0.5-0.75 0.75-1	 0.25 0.5 0.75 1
	Traffic intensity	0.2	Black, Light green and Green Orange Red Dark red	0.25 0.5 0.75 1
Hazard models	Earthquake peak ground acceleration (cm/s^2)[1]	-	100-200 200-300 300-400 400-500 500-600	0.2 0.4 0.6 0.8 1
	Fire outbreak potential[2]	-	Low risk Moderately low risk Moderately high risk High risk	0.25 0.5 0.75 1
	Proximity to liquefaction zones[3]	-	Maximum value transformation 0.75-1 0.5-0.75 0.25-0.5 0-0.25	 0.25 0.5 0.75 1
	Risk of road closure by building debris[3]	-	Low Medium High Very high	0.25 0.5 0.75 1
	Road damage risk[3]	-	Low Medium High Very high	0.25 0.5 0.75 1

[1] This hazard indicator is applied to all risk assessments, except the systemic risk assessment
[2] This hazard indicator is applied to the socioeconomic risk assessment only
[3] This hazard indicator is applied to the systemic risk assessment only

The categories and corresponding standardization of the road width as presented in Table 5 are thought to be appropriate based on a comparison between the widths of the roads in the case study area according to the ‘YolOrtaHat_itrf96’ data and the characteristics of the roads according to the fieldwork.

The standardization of the three vulnerability indicators: the ‘percentage of people over 65 years old’, the ‘percentage of low-education levels’ and the ‘percentage of low-income levels’, is based on the standardization used by Yüce & Arun (2012) (Table 6). This is a study on the vulnerability levels in another district of Istanbul, the Avcilar district. That is why it is assumed to be applicable to this study as well.

Table 6: Standardization of socioeconomic vulnerability indicators of building occupants. Source: Yüce & Arun (2012, p. 6)

	Percentage of	Vulnerability level group			
		(1) Low	(2) Medium	(3) High	(4) Highest
1	Population over age 65	%0–8	%8–13	%13–20	%20–67
2	No high school diploma	%0–13	%13–22	%22–33	%33–80
3	Low household income	%0–5	%5–11	%11–27	%27–100
4	Rental house	%0–17	%17–35	%35–56	%56–100
5	Single parent with child families	%0–8	%8–11	%11–25	%25–70

The determination of the risk awareness and risk preparedness in the neighbourhoods of the case study area is based on the study of Ugur et al. (2018) which presents the social vulnerability of each neighbourhood in Istanbul based on a survey. In this study, two aspects of social vulnerability are considered. The first is the capacity to cope with the consequences of the disaster, the second are the characteristics of the person and the society before they encounter the danger which affect their level of exposure to the disaster. The study was designed on a household-based, neighbourhood scale to cover the whole of Istanbul. The survey was and was carried out in 41,093 household with a total of 139,688 people in 955 neighbourhoods to assess the social vulnerability of each neighbourhood. The surveys were carried out simultaneously online, with telephones and with field controls. This took 125 days from 17 June 2017 till 30 November 2017. After analysing the results of the questionnaires, social vulnerability indices were calculated that represent the neighbourhoods in Istanbul.

Indicators that describe travel time to the critical facilities, distance to the liquefaction zones, solid to void ratio and population density are standardized using the maximum value transformation as described in Section 2.2.4. This is considered appropriate for this study.

Based on the additive normalisation indicator-based approach for the vulnerability and risk assessments as described in Section 2.2.4, the vulnerability indicators which are standardized according to Table 5, are combined using Equation 3. The resulting Vulnerability Indices represent from 0 to 1, low to high vulnerability. In this study, each indicator has equal weights, because no literature has been found to justify other weights. Besides this, according to Yoon (2012), most vulnerability studies do not apply weights, because indicators are considered independent and of equal importance. The same equation is applied to determine the overall hazard index. Which hazard is included depends on the type of risk assessments to which the overall hazard index is applied to. After this, the vulnerability and corresponding hazard indices are multiplied according to Equation 1 to acquire the risk indices. Both the vulnerability and risk scores are standardized by applying the min-max rescaling technique as described in Section 2.2.4, in which X_{min} and X_{max} in the equation are the lowest and highest possible indices from the vulnerability and risk assessments, respectively. After this, the standardized vulnerability and risk values are categorized shown in Table 7. The results of the socioeconomic, road and systemic vulnerability and risk assessments are presented in Sections 4.2.1, 4.2.2 and 4.2.4, respectively.

Table 7: Classification of vulnerability and risk indices. Source: Author (2022)

Vulnerability and risk indices	Classification
Index ≤ 0.25	Low
Index > 0.25 and Index ≤ 0.5	Medium
Index > 0.5 and Index ≤ 0.75	High
Index > 0.75 and Index ≤ 1	Very high

3.4.3 The building physical vulnerability and damage degree assessment using the EMS-98 Macroseismic method

In order to determine the physical vulnerability and damage of the buildings the EMS-98 Macroseismic method (LM1) as proposed by the Risk-UE project (Milutinovic & Trendafiloski, 2003) is applied. This method is also adopted by Giovinazzi & Lagomarsino (2004), Pavić et al. (2019) and Redweik et al. (2017). The reason for using this method is that it is applicable and reliable to all the regions in Europe, because it is based on the EMS-98 Macroseismic scale. This is not the case for other methods, because these are strongly connected to the data used for the method, making it difficult to generalize for other regions. This Macroseismic method is based on the EMS-98 intensity scale, because it is the most recent scale that will probably be used in Europe in the future, and because it defines the building typologies and damage degrees with great quality (Giovinazzi & Lagomarsino, 2004).

In this method, six vulnerability classes (A to F) of decreasing vulnerability are introduced. The vulnerability classes are initially derived from the typology of a building. The Macroseismic method distinguishes between masonry, reinforced concrete, wooden and steel buildings. Next to the typology of a building, it is possible that its vulnerability is affected by other constructive or structural characteristics which change its seismic behaviour. That is why, in this method Equation 4 has been introduced to determine an overall Vulnerability Index ($\overline{V_l}$) of a building based on its typology and the other related factors:

$$\bar{V}i = Vi^{*} + \Delta Vr + \Delta Vm \tag{4}$$

Here, V_i * is the typology vulnerability index, ΔV_r is the Regional Vulnerability Factor and ΔV_m is the Behaviour Modifier Factor representing the other factors that affect the vulnerability of a building.

According to the EMS-98 vulnerability tables presented by Giovinazzi & Lagomarsino (2004), Milutinovic & Trendafiloski (2003) and Redweik et al. (2017) (Appendix B), steel structures are least vulnerable with vulnerability class E and a corresponding vulnerability score of 0.363. After this come reinforced concrete structures which show to have lower vulnerability values and classes than for example masonry. Based on the building typology data for Fatih used by JICA & IMM (2002), it can be said that these buildings have reinforced concrete frames. Thus, they are given a vulnerability score of 0.442. The vulnerability score of reinforced concrete structures depends on the design building code applied to the structure. This will be introduced later in this section. Wooden structures which are considered slightly more vulnerable than reinforced concrete structures with a vulnerability score of 0.447. Lastly, masonry buildings are most vulnerable. According to an academic at the Istanbul Technical University, the main typology of masonry buildings in Fatih should be distinguished based on age of construction. Masonry buildings constructed before 1950 are accepted to have wooden slabs, masonry buildings constructed after 1950 are accepted to have concrete slabs. Based on this, the best estimate applicable to this study is that masonry buildings constructed before 1980 according to the data can be considered masonry buildings with wooden slabs with a vulnerability score of 0.74, while masonry buildings constructed after 1980 can be considered masonry buildings with concrete slabs with a vulnerability score of 0.616. The buildings belonging to the categories 'others' and 'unidentified' are assumed to be the same as masonry buildings with wooden slabs, because it is considered best to apply the worst-case scenario and therefore use the most vulnerable buildings in the area.

The range for the values of the vulnerability indices for the different construction types is quite significant. In some parts of Europe, the traditional construction techniques of the buildings might cause the vulnerability to reduce or increase. That is why the Regional Vulnerability Factor is introduced. One can modify the vulnerability indices based on expert judgement or based on available historically observed vulnerability to be able to represent the local building typologies better (Giovinazzi & Lagomarsino, 2004; Milutinovic & Trendafiloski, 2003). Since there was no reason to do so, the Regional Vulnerability has been excluded from this assessment.

An overview of the Behaviour Modifier Factors which affect the vulnerability of the buildings is provided in Table 8. This table is based on existing tables from Giovinazzi & Lagomarsino (2004), Milutinovic & Trendafiloski (2003) and Redweik et al. (2017) which can be found in Appendix B. Note that some factors are not included such as the building maintenance level, because the required data was not available.

Table 8: Overview of Behaviour Modifier Factors included in this study. Source: Author (2022)

Behaviour Modifier Factor	**Option**	**Masonry**	**Reinforced concrete**			**Wood**	**Steel**	**Other**
			Pre or Low code	Moderate code	High code			
Age/code level			+0.16	0	-0.16			
Number of stories	Low (1-2) Medium (3-5) High (>6)	-0.02 +0.02 +0.06	-0.04 0 +0.08	-0.04 0 +0.06	-0.04 0 +0.04	-0.02 +0.02 +0.06	-0.02 +0.02 +0.06	-0.02 +0.02 +0.06
Vertical Irregularity		+0.02	+0.04	+0.02	0	+0.02	+0.02	+0.02
Aggregate building: position	Detached Middle Header	0 -0.04 +0.06				0 -0.04 +0.06	0 -0.04 +0.06	0 -0.04 +0.06
Aggregate building: elevation*	1 2 3 4 5	-0.04 -0.02 0 +0.02 +0.04				-0.04 -0.02 0 +0.02 +0.04	-0.04 -0.02 0 +0.02 +0.04	-0.04 -0.02 0 +0.02 +0.04

*(1) Adjacent buildings are higher (2) An adjacent buildings is higher and another at the same level (3) Adjacent building have the same level (4) An adjacent buildings is lower and another at the same level or is higher (5) Adjacent buildings are lower.

The age of the building can represent the seismic design codes which are being applied to construct the buildings. According to Gunes (2015) and Ilki & Celep (2012), the first national seismic design code in Turkey was released in 1944. It was changed seven times afterwards until the current version of 2007. Mostly prescriptive rules were included in the earlier versions of the seismic design codes. Only after the updated versions of 1975 and especially 1998 in which the principles of ductility and capacity design were introduced, the design codes started to resemble modern seismic codes. The currently used 2007 version of the seismic design codes in Turkey is the first to include the evaluation of the newly built constructions. This was needed, because before that time the construction of buildings was not always done according to the seismic design codes that were applied during those time. Consequently, the grouping of buildings with respect to age is generally done by distinguishing between pre-1980 constructed buildings (pre or low code), buildings constructed between 1980 and 2000 (moderate code) and post-2000 constructed buildings (high code). The same grouping is used in this study. The effect of the codes are not applied to masonry buildings. The reason for this is that such buildings are often not treated as engineered structures in many parts of the world, because design rules of masonry building may not be included in the codes. In Turkey, only the code of 2007 includes rules for the design of unreinforced masonry buildings. Hence, in general, one cannot relate the design codes to the masonry buildings (Bal et al., 2008). Depending on the use of buildings the vulnerability can also be affected. The change in usage of the building introduce subsequent modifications. For example when the ground floor is changed for a shop it could weaken the structural integrity as structural element might be removed and with that irregularity is caused. Such changes belong to vertical irregularity (Grünthal & Schwarz, 1998). Buildings that are public or commercial are assumed to have undergone changes that cause such vertical irregularities. Besides this, adjacent buildings can affect each other. The way that they affect each other depends on two things: their relative position in the building block and height difference between the different buildings. A detached building has no increased vulnerability due to its position, a building that is located in between other buildings is assumed to be less vulnerable regardless of whether it is located at a corner or in the middle, and a building that has the position 'header' is most vulnerable. In such cases, one side of the building is attached to another causing only that side to be 'anchored'. This causes an irregularity in stiffness which result in more damage (Grünthal & Schwarz, 1998). Lastly, building that are adjacent can have difference building heights. A difference in building height of buildings can result in a pounding effect between the buildings, resulting in more damage than expected. This is caused by the difference in the frequency of vibrations of the buildings during an earthquake (Grünthal & Schwarz, 1998; Malladi, 2012). How this effects the vulnerability of the buildings is determined by Ademovic et al. (2022) and Hadzima-Nyarko et al. (2016). The behaviour modifier factors of the latter two indicators were only considered for masonry building in the Macroseismic method. Due to the lack of information about the behaviour modifier factors of wooden, steel and other structures, these are assumed to be the same as for masonry buildings. The overall Behaviour Modifier score (ΔV_m) which modifies the vulnerability indices for the buildings can be calculated by summing the different Behaviour Modifier Factors (V_m): $\Delta V_m = \sum V_m$. After this, Equation 4 can be used to determine the vulnerability indices of the buildings. The results are classified according to the vulnerability classes as determined by Milutinovic & Trendafiloski (2003) (Figure 16).

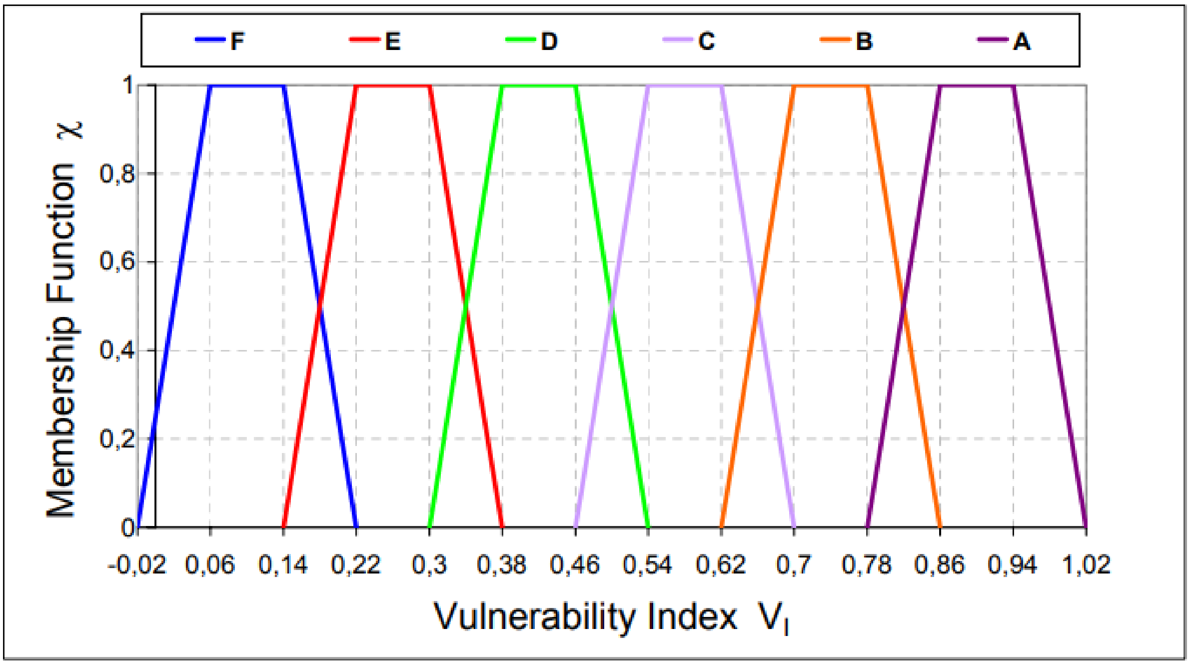
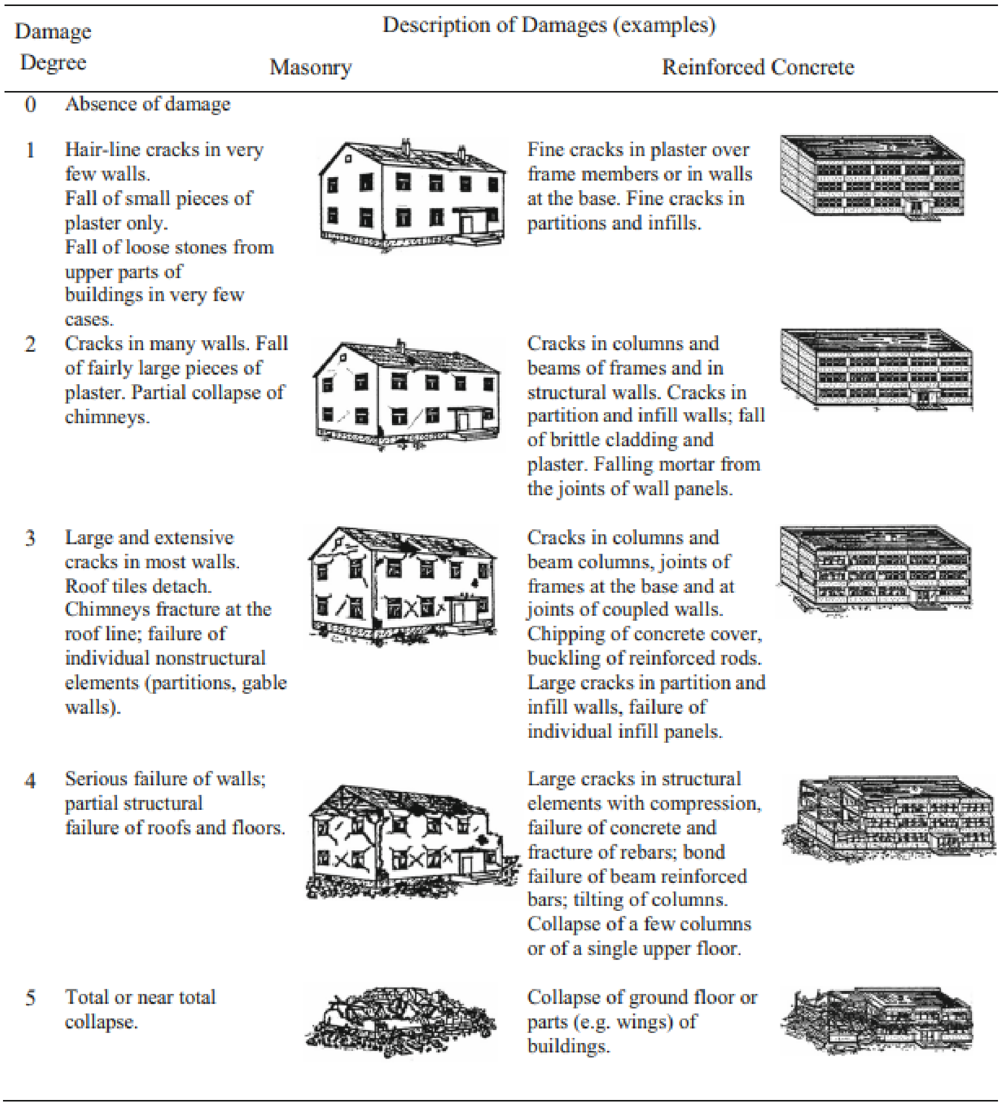


Figure 16: Membership function of the vulnerability indices. Source: Milutinovic & Trendafiloski (2003, p. 28)

As presented by Milutinovic & Trendafiloski (2003) and Giovinazzi & Lagomarsino (2004), the calculated vulnerability indices can be correlated to a damage degree for a certain intensity scenario. This can be done using Equation 5 in which the damage degree (μ_D) is a function of the Macroseismic intensity (I) and the vulnerability index (V_i). This same approach is used by Redweik et al. (2017) and Pavić et al. (2019).

$$\mu_D = 2.5\left(1 + tanh\left(\frac{I + 6.25\bar{V}_i - 13.1}{2.3}\right)\right) \tag{5}$$

The results of this equation are rounded to be able to agree with the Macroseismic damage scale as is done by Redweik et al. (2017). This scale distinguishes between five damage grades for buildings as illustrated in Figure 17.



Damage Degree	Description of Damages (examples): Masonry	Reinforced Concrete
0	Absence of damage	
1	Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.	Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
2	Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.	Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
3	Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual nonstructural elements (partitions, gable walls).	Cracks in columns and beam columns, joints of frames at the base and at joints of coupled walls. Chipping of concrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
4	Serious failure of walls; partial structural failure of roofs and floors.	Large cracks in structural elements with compression, failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
5	Total or near total collapse.	Collapse of ground floor or parts (e.g. wings) of buildings.

Figure 17: EMS-98 Damage scale description for masonry and reinforced concrete buildings. Source: Redweik et al. (2017, p. 322)

Gómez et al. (2015) determined the following relation (Equation 6) between the Peak Ground Acceleration (PGA) and the EMS-98 intensity scale based on their own regional database from Turkey.

$$I_{EMS-98} = 0.132 + 3.884 \log PGA_{max} \quad (6)$$

Here, $I_{EMS\text{-}98}$ is the Macroseismic intensity and PGA_{max} is the maximum Peak Ground Acceleration. The gathered PGA data is converted to the Macroseismic intensity scale using this equation to be able to use it in the function which determines the damage degrees of the buildings. While matching the physical vulnerability of the buildings with the PGA, a spatial join was done in GIS. Here, the PGA value which overlaps a building footprint is joint. The hazard models from JICA & IMM (2002) on the fire outbreak and liquefaction potential are excluded from the calculation of the building damage degrees, because liquefaction is shown to only occur outside of the case study area and the fire outbreaks are a consequence of building damage and should therefore not be included in the calculation of building damage. Appendix C provides an overview on the descriptions of the different EMS-98 Macroseismic intensities and quantification of the related vague definitions of ‘few’, ‘many’ and ‘most’ as used in the descriptions. The results of the application of the Macroseismic method to the buildings in the case study area are presented in Section 4.2.3.

3.4.4 Road closure analysis based on building damages

The road closure analysis of Cakti et al. (2019) relies on the number of buildings in a 'complete damage state' and the road width (number of lanes). They use the following assumption to determine the blocking of roads caused by debris from buildings: Completely damaged low-rise buildings (1 to 4 storeys) can cause total closure in one-lane roads and partial closure in two-lane roads. Completely damaged mid-rise buildings (5 to 8 storeys) can cause total closure in one- and two-lane roads and partial closure in three-lane roads. Completely damaged high-rise buildings (9 to 19 storeys) can cause total closure in one-, two- and three-lane roads and partial closure in four-lane roads. In the study of Cakti et al. (2019), one lane is considered to be 3m wide. Therefore, this lane width is also applied to determine the extent of the debris in this study. According to FEMA (2003), which is the technical manual used for the road closure analysis of Cakti et al. (2019), a reinforced concrete building with moment frames that is completely damaged can be defined as: 'The structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability' (FEMA, 2003, p. 5-19). According to Milutinovic & Trendafiloski (2003), the fourth damage grade of FEMA (2003) ('completely damaged buildings') can be correlated to damage grade 4 and 5 according to the EMS-98 damage scale. Based on this, the aforementioned assumption will be applied to buildings with a damage degree of 4 (heavily damaged) and 5 (collapsed). It has to be noted that the amount of debris can differ with increasing damage degree and depending on the typology of the building. However, this should not affect the final outcomes of the analysis significantly. It is possible that buildings which are near each other create overlapping debris buffers. When this is the case, an increasing number of overlapping layers is assumed to represent an increasing likelihood of the debris to occur at that location and an increasing size of the debris making it less easy to remove. The steps to determine the road closure risk using GIS are shown in Figure 18. The results show the extent of road blockage per road segment. These values are thought to represent the risk that the road segments become blocked and with that impassible. The results of this analysis are presented in Section 4.2.3.

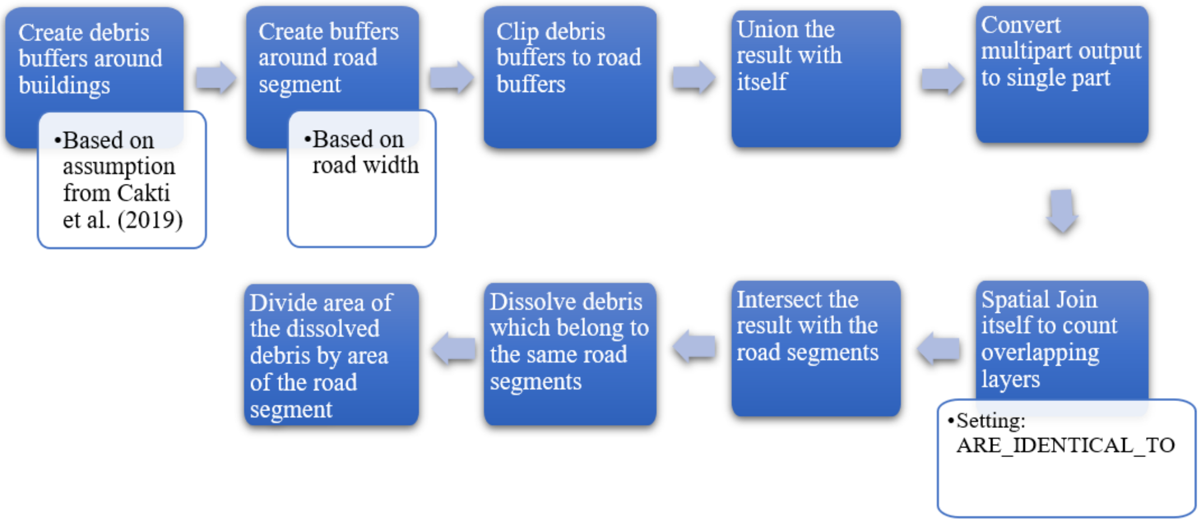


Figure 18: Workflow in GIS to determine the road closure risk. Source: Author (2022)

3.5 Procedural 3D modelling

The building footprints and road network data that includes among others the vulnerability and risk indices determined by the vulnerability and risk assessments are imported as shapefiles into CityEngine to proceed with the procedural 3D modelling and the analysis of the results. Several CGA rules were implemented to automatically generate the 3D models of each building and shapes of each road from their respective footprints and to provide each building and road segment with a coloured (and textured) appearance. Realism was not considered a priority, because the main aim of the 3D model is to be explored for the analysis of the vulnerability, risk and identified disruptions. That is why, the appearance of the buildings is only coloured, not textured to clearly distinguish between the different vulnerability and risk levels. Some texture is applied to the streets to better represent the type and width of the roads within the case study area.

The levels of Detail (LoD) defined in the CityGML of the Open Geospatial Consortium (OGC) are used for the 3D modelling, because this is considered the international standard. For this study, LoD1 was used considering the available data. Consequently, the 3D building models are created by applying a CGA rule that extrudes the building footprints based on the building height information. Additionally, the CGA rule applies a colour scheme to the buildings from green to red representing low to high vulnerability or damage degree based on the corresponding attributes of each building. Then, the shapefile of the road network in the case study area is imported. A road network with intersection, sidewalks, etc. is automatically created based on the imported road polylines. The resulting road network is manually adjusted where necessary to remove errors and make it more realistic (e.g. overlapping streets are separated). After the road network has been created, ESRI's 'Street_Modern_Standard.cga' rule is applied to the road network. This is an existing CGA created by ESRI that generates textured roads. It for example applies centrelines, crosswalks, etc. to the roads to make it look visually more realistic. This ruleset has been adjusted slightly by applying the colour scheme based on the vulnerability and risk attributes of the road network to the 'brightness' of the textured road lanes. Consequently, the different road segments are coloured depending on their corresponding attributes, while their applied texture remains intact. Lastly, the debris shapefile is imported as well. By applying a CGA rule the layer is extruded and coloured with a colour scheme from white to red depending on the number of overlapping debris layers which, as mentioned in Section 3.4.4, presents the likeliness and size of the debris. The resulting 3D models are presented in Sections 4.2.3. For the purpose of sharing the 3D models, a web scene has been created. This is done by first duplicating the created building, road and debris 3D models and applying the related colour scheme depending on the different vulnerability and risk indices. All of the models are then exported using the CityEngine web scene export function. An overview of all created 3D models is shown in Figure 19.

Figure 19: Screenshot of the CityEngine tool with an overview on the created 3D models. Source: Author (2022)

3.6 A comparison study based on literature review

In order to evaluate the results and find out what the answer is to the main research question, the results of the vulnerability and risk assessment and their visualisation in 3D are compared to existing two-dimensional analyses. It has been decided to compare the socioeconomic vulnerability to the social vulnerability as determined by Ugur et al. (2018), because this is research is based on extensive survey work on the social vulnerability that exists within Istanbul and clearly represent the results on neighbourhood-level. The building damages as determined by this study are compared to the results as presented by JICA & IMM (2002) which focuses on the potential damage that can occur in buildings, roads and other lifelines as a result of the same earthquake event. In terms of potential disruptions, both JICA & IMM (2002) and Cakti et al. (2019) analysed the risk of road closure due to debris from buildings in Istanbul. Their results are used as comparison material to evaluate the road closure analysis of this study. Based on this comparison study, a conclusion is drawn on what the additional insights of using 3D modelling in disaster risk analysis are. The results of this comparison study can be found in Section 5.1.

4 Results

In Section 4.1, the data preparation steps of the vulnerability indicators as introduced in Section 3.4 are described. After applying the proposed methods for the vulnerability and risk assessments to the prepared indicators and the visualisation of some of the results in three dimensions using procedural 3D modelling, several 2D layers and 3D models were created which will be presented and analysed in section 4.2. This section also analyses the potential disruptions within the case study area that are identified in Section 2.1.4. Lastly, structural and non-structural interventions are suggested in Section 4.3 based on the vulnerability and risk in the case study area, and the potential disruptions.

4.1 Data Preparation for the vulnerability and risk assessments

4.1.1 Preparation of the socioeconomic vulnerability indicators

Risk awareness and preparedness

The survey work done by Ugur et al. (2018) included among others questions about the risk awareness and risk preparedness in Istanbul. The answers to these questions are used to determine the risk awareness and risk preparedness of the people in the case study area. Based on the questions and answers in Table 9 and Table 10, it can be said that a significant part of the people in the case study area is aware about the risk to earthquakes, especially in Sehremini and Topkapi. Also, in comparison with the rest of Fatih, these neighbourhoods seem to have a better awareness about this risk. A similar pattern can be found looking at the level of knowledge about the potential earthquakes and their corresponding impact (Table 11). This shows that Sehremini and Topkapi do have a relatively high understanding about the earthquakes with 85.5% and 64.6% knowing at least somethings, respectively, in comparison to Faith (44.2%) and Istanbul (55.0%). In contrast, Molla Gürani shows to be much less knowledgeable about earthquakes with only 20.4% knowing at least something, leaving 79.6% knowing just a little bit of which 28.6% knows nothing at all. Consequently, the risk awareness of the people in Molla Gürani can be classified as low. For Topkapi this is medium and for Sehremini this is high. The difference between Sehremini and Topkapi is caused by the difference in how many people know most things about the earthquakes which for Sehremini is significantly higher than for Topkapi. For both there is still room for improvement in terms of risk awareness, which why they are not considered to have very high risk awareness.

A similar pattern can be found looking at what percentage of the people in the neighbourhoods took precautions (

Table 12) and how prepared they feel for an earthquake event (Table 13). A combination of both these indicators is assumed to represent risk preparedness. Sehremini and Topkapi have taken more precautions (75.0% and 64.6%, respectively) and feel more prepared than the other regions. However, with only 27.1% and 29.4% of the people in Sehremini and Topkapi, respectively, feeling prepared for earthquakes, they are considered to have medium risk preparedness. In Molla Gürani people have taken very few precautions (28.6%) and they do not feel prepared (95.9% of the people do not feel prepared). These numbers represent very low preparedness levels, also in comparison to the other regions. That is why Molla Gürani is considered to have low risk preparedness.

Table 9: Answers to the question: 'Do you think there will be an earthquake in Istanbul in the near future?' from Ugur et al. (2018). Source: Author (2022)

Do you think there will be an earthquake in Istanbul in the near future?			
Answer	Yes (%)	No (%)	I don't know/ I have no idea (%)
Şehremini	83.3	4.2	12.5
Topkapi	79.2	2.1	18.8
Molla Gürani	63.3	8.2	28.6
Fatih	56.7	10.0	33.4
Istanbul	55.9	10.3	33.7

Table 10: Answers to the question: 'Do you think that in case of an earthquake, your neighbourhood will be affected by this earthquake?' from Ugur et al. (2018). Source: Author (2022)

Do you think that in case of an earthquake, your neighbourhood will be affected by this earthquake?			
Answer	Yes (%)	No (%)	I don't know/ I have no idea (%)
Şehremini	87.5	8.3	4.2
Topkapi	81.3	12.5	6.3
Molla Gürani	69.4	16.3	14.3
Fatih	62.1	16.8	21.1
Istanbul	56.2	23.8	20.0

Table 11: Answers to the question: 'If you were to give a score between 1 and 5 for your level of knowledge about the earthquake, how many points would you give?' from Ugur et al. (2018). Source: Author (2022)

If you were to give a score between 1 and 5 for your level of knowledge about the earthquake, how many points would you give?					
Answer	I don't know anything (%)	I know a little (%)	I know (%)	I know most things (%)	I know everything well (%)
Şehremini	2.1	12.5	43.8	22.9	18.8
Topkapi	12.5	22.9	37.5	16.7	10.4
Molla Gürani	28.6	51.0	18.4	0.0	2.0
Fatih	25.5	30.3	30.7	9.6	3.9
Istanbul	14.5	30.5	40.1	11.6	3.3

Table 12: Answers to the question: 'Have you taken any precautions against the possibility of an earthquake?' from Ugur et al. (2018). Source: Author (2022)

Have you taken any precautions against the possibility of an earthquake?		
Answer	Yes (%)	No (%)
Şehremini	75.0	25.0
Topkapi	64.6	35.4
Molla Gürani	28.6	71.4
Fatih	42.6	57.4
Istanbul	52.0	48.0

Table 13: Answers to the question: 'How prepared do you feel for a possible earthquake situation?' from Ugur et al. (2018). Source: Author (2022)

How prepared do you feel for a possible earthquake situation?				
Answer	I am not prepared at all (%)	I'm not prepared (%)	I'm Prepared (%)	I am fully prepared (%)
Şehremini	37.5	35.4	25.0	2.1
Topkapi	35.4	35.4	25.0	4.2
Molla Gürani	24.5	71.4	4.1	0.0
Fatih	46.7	39.5	13.2	0.6
Istanbul	38.4	43.7	16.8	1.0

Percentage of people with low-income levels

Table 14 presents the results from a question asked in the survey of Ugur et al. (2018) about the average monthly income of the households in Istanbul. The minimum wage in Turkey in 2017 was 1777.50 Turkish Lira (countryeconomy.com, 2022). Thus, it is assumed that the people who earn less than 2000 Turkish Lira can be categorized as being part of the low-income socioeconomic group. The reason for choosing the minimum wage in 2017 is that the data on income levels is gathered from a survey that was done in 2017.

Table 14: Answers to the question: 'Which of the following groups does the average monthly income of your household from any source fall into?' from Ugur et al. (2018). Source: Author (2022)

Which of the following groups does the average monthly income of your household from any source fall into?									
Answer	< 1000 TL (%)	1001-2000 TL (%)	2001-3000 TL (%)	3001-4000 TL (%)	4001-6000 TL (%)	6001-8000 TL (%)	8001-10000 TL (%)	> 10000 TL (%)	Low-income (%)
Şehremini	2.1	20.8	58.3	16.7	2.1	0.0	0.0	0.0	22.9
Topkapi	4.2	37.5	41.7	16.7	0.0	0.0	0.0	0.0	41.7
Molla Gürani	0.0	28.6	51.0	14.3	6.1	0.0	0.0	0.0	28.6
Fatih	4.6	35.0	34.6	17.4	6.2	1.7	0.4	0.2	39.6
Istanbul	1.6	26.2	34.3	21.7	10.6	3.6	1.2	0.8	27.8

Table 14 shows that Topkapi is a neighbourhood with very low-income levels, because 41.7% of the people can be categorized as such. Therefore, the low-income levels of Topkapi can be classified as having the highest impact on the vulnerability according to Table 6. Sehremini and Molla Gürani are less vulnerable than Topkapi in this regard with 22.9% and 28.6% low-income levels, respectively. This can also be said when compared to Fatih in general, but it should be noted that Fatih belongs to the poor areas of Istanbul, because its percentage of low-income people is significantly higher than the one of Istanbul. This is logical since the area is inhabited by low-income newcomers as stated by Atun & Menoni (2014). The low-income levels of Sehremini can be classified as having a high impact on the vulnerability. Lastly, although the low-income levels in Molla Gürani should be considered to have the highest impact on the vulnerability, for this case it is considered to be more appropriate to apply a high impact on the vulnerability, because it is very close to that level and is significantly different from the percentage of low-income in Topkapi.

Percentage of people with low education levels

The dataset 'Istanbul population_2020' distinguishes between the following education levels: Unknown, Illiterate, Literate but did not finish a school, Primary school graduate (the first 5 years of primary education), Middle school or equivalent graduate (the last 3 years of primary education), Primary education graduate (the entire 8-years), High school or equivalent graduate, college or faculty graduate, Master graduate and Doctorate graduate. Duzgun et al. (2011) states that the level of education increases vulnerability when the education level is primary education or lower. Similarly, Cutter et al. (2009) and Yüce & Arun (2012) state that the number of people with an education level lower than high school increase vulnerability. Based on this it can be said that for this study, the people with an education level of illiterate, literate but did not finish a school, primary education graduate, primary school graduate and middle school or equivalent graduate are causing the vulnerability to increase. The percentage of people with a low education level is calculated by dividing the number of people with the abovementioned education levels by the total number of people in the neighbourhoods. The results are that the percentage of low-education in Sehremini is 45.2%, in Topkapi is 40.3% and in Molla Gürani is 43.0%.

Percentage of people over 65 years old

Using the dataset 'Istanbul population_2020', the percentage of population which is older than 65 years is calculated by dividing the number of people older than 65 years by the total population of each neighbourhood. The results show that the percentage of the population over 65 years old for Sehremini is 17.8%, for Topkapi this is 13.2% and for Molla Gürani this is 15.5%.

Population density

The population density has been determined by dividing the total population in each neighbourhood from the dataset 'Istanbul population_2020' by the area of each neighbourhood. The population density in Topkapi is 16,653 people per km^2, in Molla Gürani this is 34,782 people per km^2 and in Topkapi this is 44,967 people per km^2,

4.1.2 Preparation of road vulnerability indicators

Road width

In the dataset 'YolOrtaHat_itrf96', the major roads are usually represented by 2 different polylines representing the different traffic directions of the major roads. However, both lines have been given the width of the total width of the major roads. That is why roads with a larger width than 16m have been divided by 2. This can be justified by looking at roads in Google maps and by the pictures from the fieldwork. Roads classified as 'Inner roads' had a width of 0m. Based on Google maps it can be said that each inner road can provide space for 1 to 2 cars. That is why these roads are given a width of 5m. Sidewalks also have a width of 0m. Nothing is changed for this case, because these are not used by traffic.

Road Maintenance level

Based on fieldwork, it can be said that all roads are of good quality and no big differences were seen in the quality of the roads. Also, the case study area is on a small scale which is all urban, not residential, industrial, etc. Thus, it can be expected that the quality of the roads are similar. Since this is the case, the maintenance level of all roads are classified as 'good'.

Road Material

According to Tung (2004), under the same peak ground acceleration, asphalt roads are likely to be damaged less than earthen roads, because the strength of the base and the surface is higher than those of earthen roads. Similarly, the study of Adafer & Bensaibi (2015) distinguishes between paved and unpaved roads. Paved roads are given a lower vulnerability score than unpaved roads. Based on these studies, all the roads in the case study area, which are either asphalt or parquet roads (paved), are considered to have low vulnerability.

4.1.3 Preparation of the building vulnerability indicators

Combining the building vulnerability indicators

The 'Yapi_itrf96' and 'DEZIM2018_BINA' datasets are combined to acquire building footprints that include the required vulnerability attributes. Figure 20 describes the steps taken in GIS to allocate the building height and construction age of the buildings to the corresponding building footprints which already included the data on the building typology and the use of the buildings.

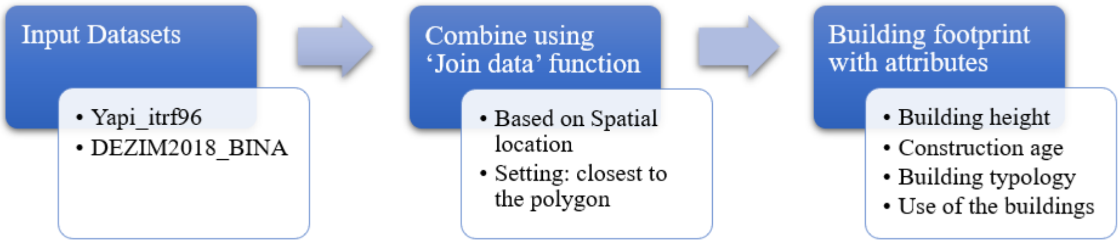


Figure 20: Workflow in GIS to combine the different building datasets. Source: Author (2022)

Difference in building height with adjacent buildings

The building footprints with attributes from the combined building datasets is used to determine the difference in height between adjacent buildings. The steps taken in GIS are described in Figure 21. The result shows for each building footprint how many buildings are adjacent and what the sum, mean, maximum and minimum difference in height is.

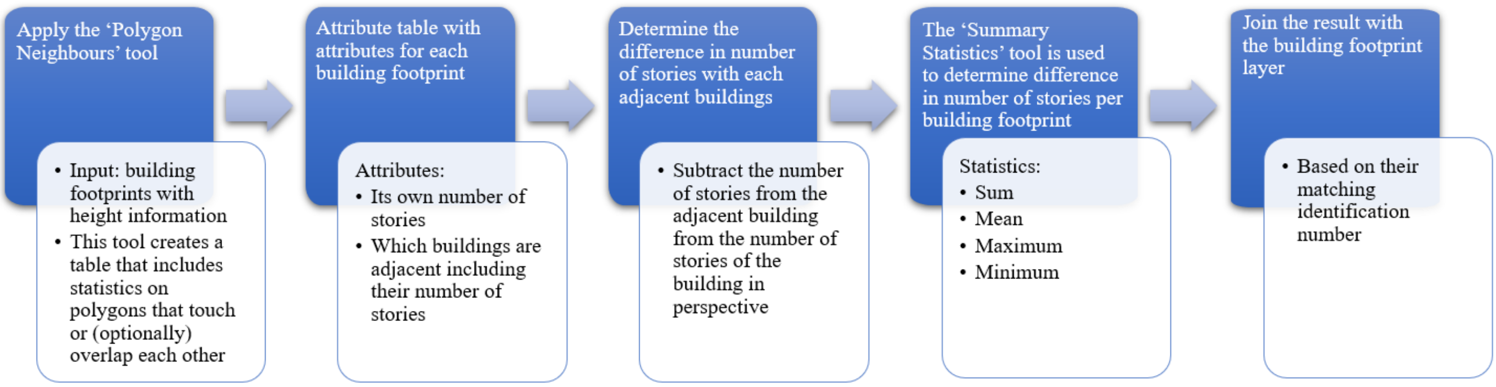


Figure 21: Workflow in GIS to calculate the difference in adjacent building height. Source: Author (2022)

4.1.4 Preparation of the systemic vulnerability indicators

Traffic intensity

The traffic intensity (from the 'SegmentDatas' dataset) was divided into traffic intensity during the morning peak hours (7:00 – 9:00) and traffic intensity during the evening peak hours (17:00 – 19:00). The two peak hours are defined based on Figure 22 in which the traffic intensity peaks are indicated. It can be seen that the traffic intensity during the peak hours in the evening is higher than during the morning. Therefore, the vulnerability analysis in this study uses the traffic intensity during the evening peak hours as an indicator.

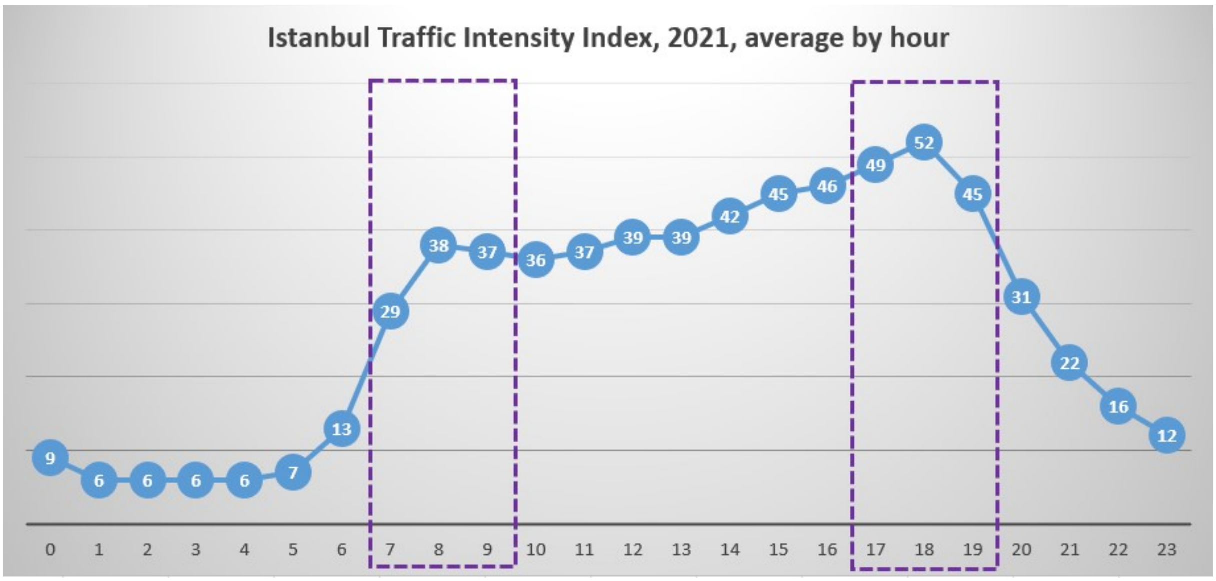


Figure 22: Traffic Intensity Index in Istanbul for 2021, averaged by hour. Source: contact person IMM (2022)

One issue is that the traffic intensity is only provided for the main road network in Fatih. Consequently, it is necessary to add the traffic intensity to the inner streets of the case study area manually. Based on fieldwork, it is decided that these are given a traffic intensity of colour 'black' which is considered to be similar to the traffic intensity of colour 'green', meaning the traffic flow on those roads is considered to be 'normal'. The reason for this is that during the fieldwork these roads were usually not found to have many driving cars, but they were filled with parked cars along the roads. As a result, it can be expected that when cars drive on those roads, they can drive at the speed limit, but not faster due to the narrow passage ways.

Solid to void ratio

The solid to void ratio is assumed to be only dependent on the presence of buildings. Consequently, the solid to void ratio in the case study area has been determined based on the relative size of the building footprints within the cells of a grid. The created grid has a resolution of 100x100m which is thought to be appropriate considering the size of the case study area and the buildings. The process in GIS is shown in Figure 23.

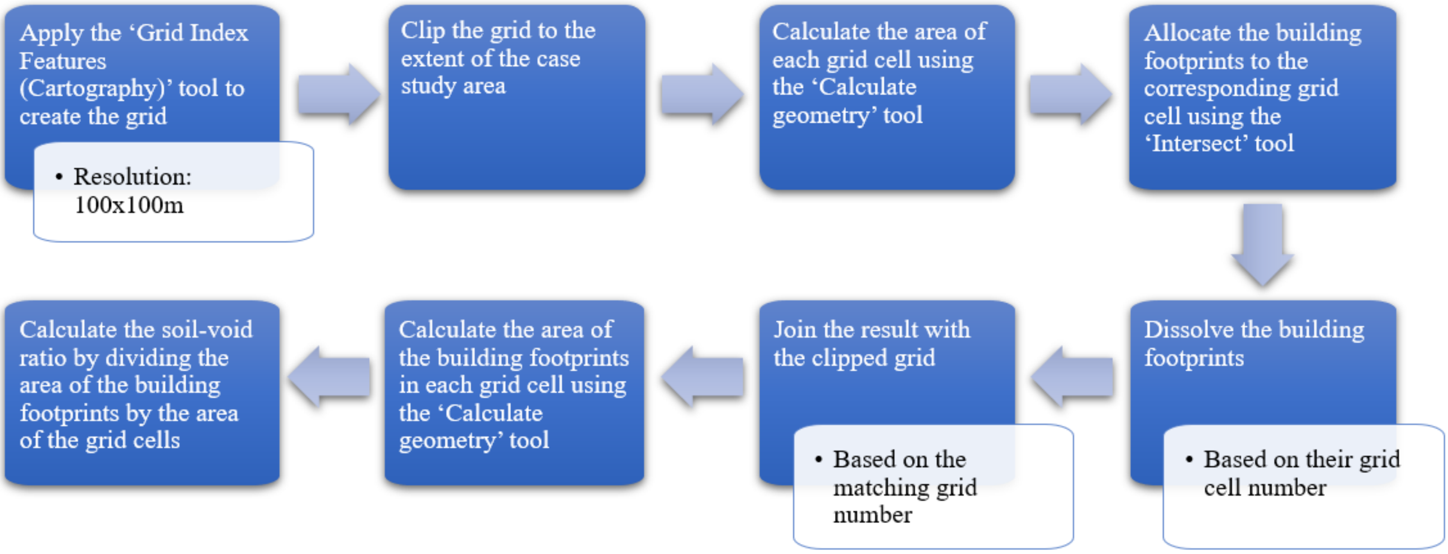


Figure 23: Workflow in GIS to determine the solid to void ratio in the case study area. Source: Author (2022)

Proximity to liquefaction zones

This indicator is prepared with a 'Closest Facility' network analysis to acquire the shortest distance for each road segment point to the closest liquefaction zone point. For this network analysis only the main roads of Fatih are considered for the calculation of the distance from the roads to the liquefaction zones, because these roads are assumed to represent the roads that comprise the traffic flow in Fatih. Thus, the impact of liquefaction on the traffic flow on the main roads is significantly more than the impact of liquefaction on narrow roads which are much less used for the traffic flow. Therefore, the road line data of the case study area (the 'YolOrtaHat_itrf96' dataset) is merged with the road line data of the main roads in Fatih (the 'SegmentDatas' dataset). This is done to cover the entire main road network in Fatih, while being more detailed within the case study area. Since the liquefaction zones are polygons and the road segments are polylines, they had to be converted to point data to be able to use them in the network analysis. The process of actions in GIS is presented in Figure 24.

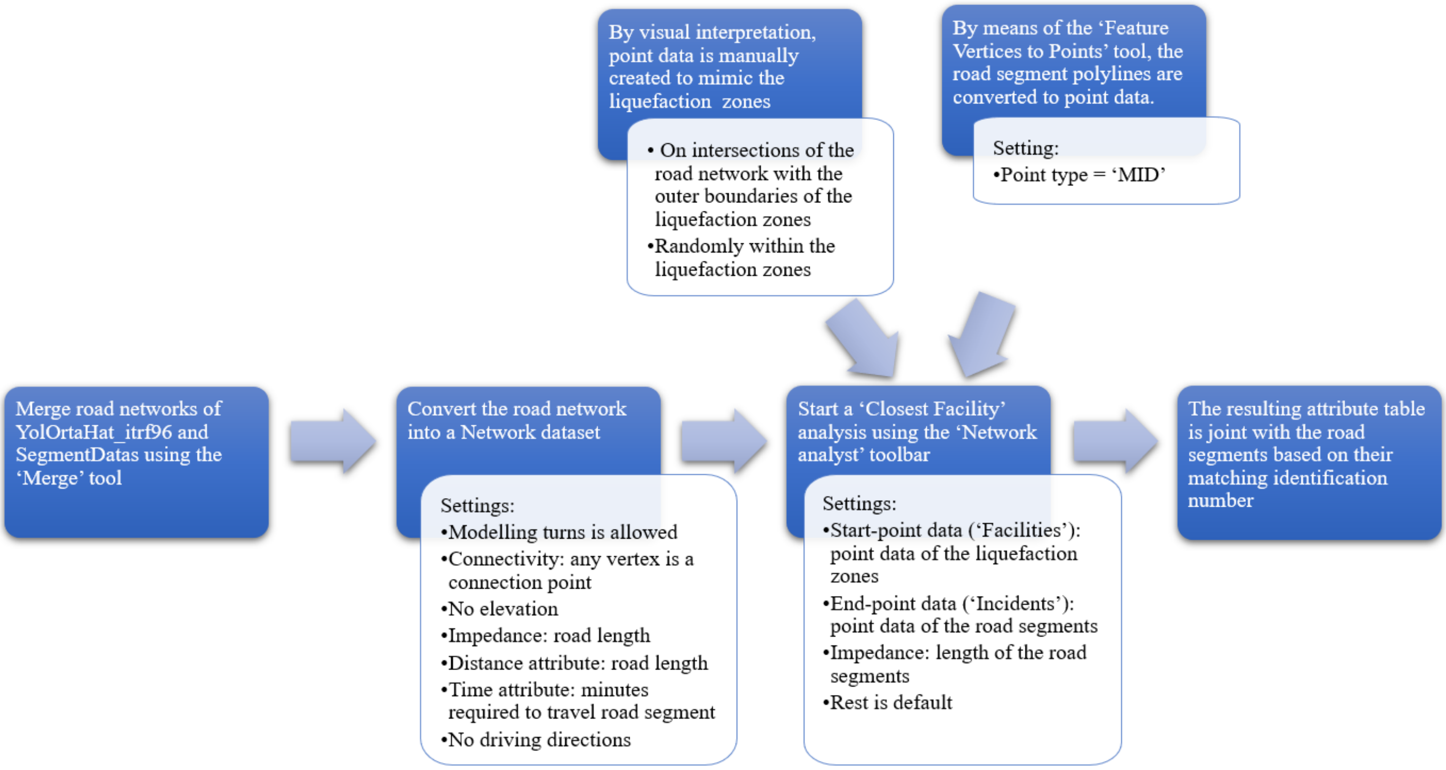


Figure 24: Workflow in GIS to determine the shortest distance from the roads in the case study area to the liquefaction zones. Source: Author (2022)

Travel time from health and critical facilities

For this network analysis, the detailed road network dataset of Fatih ('YOL') is used. In contrast to the network analysis done to determine the proximity to liquefaction zones, narrow roads are included in this network analysis. The reason for this is that these roads can be used by the emergency services to reach the disaster struck areas quicker. It is assumed that the emergency services always take the quickest route. Since the road segments are polylines, they had to be converted to point data to be able to use them in the network analysis. The workflow in GIS is presented in Figure 25.

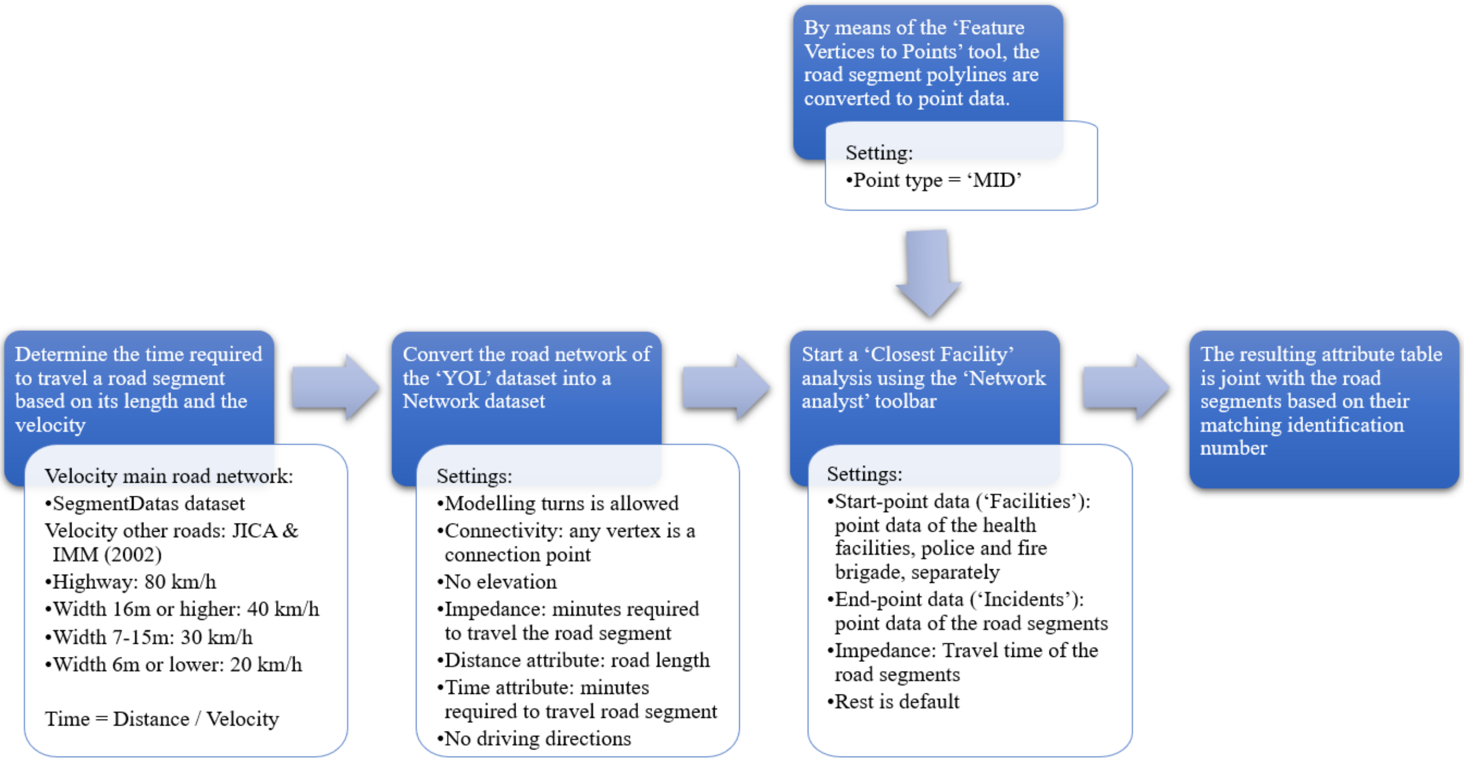


Figure 25: Workflow in GIS to determine the shortest distance from the roads in the case study area to critical facilities (heath facilities, police and fire brigade). Source: Author (2022)

4.2 Vulnerability and risk assessments

This section presents the results from the vulnerability and risk assessments. In addition, it analyses the potential for the disruptions as discussed in Section 2.1.4. Section 4.2.1 presents the socioeconomic vulnerability and risk in the case study area and describes the corresponding potential disruptions. Section 4.2.2 describes the road vulnerability and risk. Section 4.2.3 presents the building vulnerability and risk, together with the cascading road closure risk. Lastly, Section 4.2.4 discusses the systemic vulnerability and risk for the accessibility of emergency services.

4.2.1 Socioeconomic vulnerability and risk

By applying the additive normalisation indicator-based method to the socioeconomic indicators, the socioeconomic vulnerability is determined. Figure 26 shows the results for the case study area. Topkapi and Sehremini both have a high socioeconomic vulnerability. Molla Gürani is most vulnerable of the three neighbourhoods being classified as having a very high socioeconomic vulnerability. The difference between the neighbourhoods can mainly be attributed to the difference in risk awareness and risk preparedness. Since Molla Gürani has a lower risk awareness and risk preparedness it is determined to be more socioeconomically vulnerable than the other two neighbourhoods.

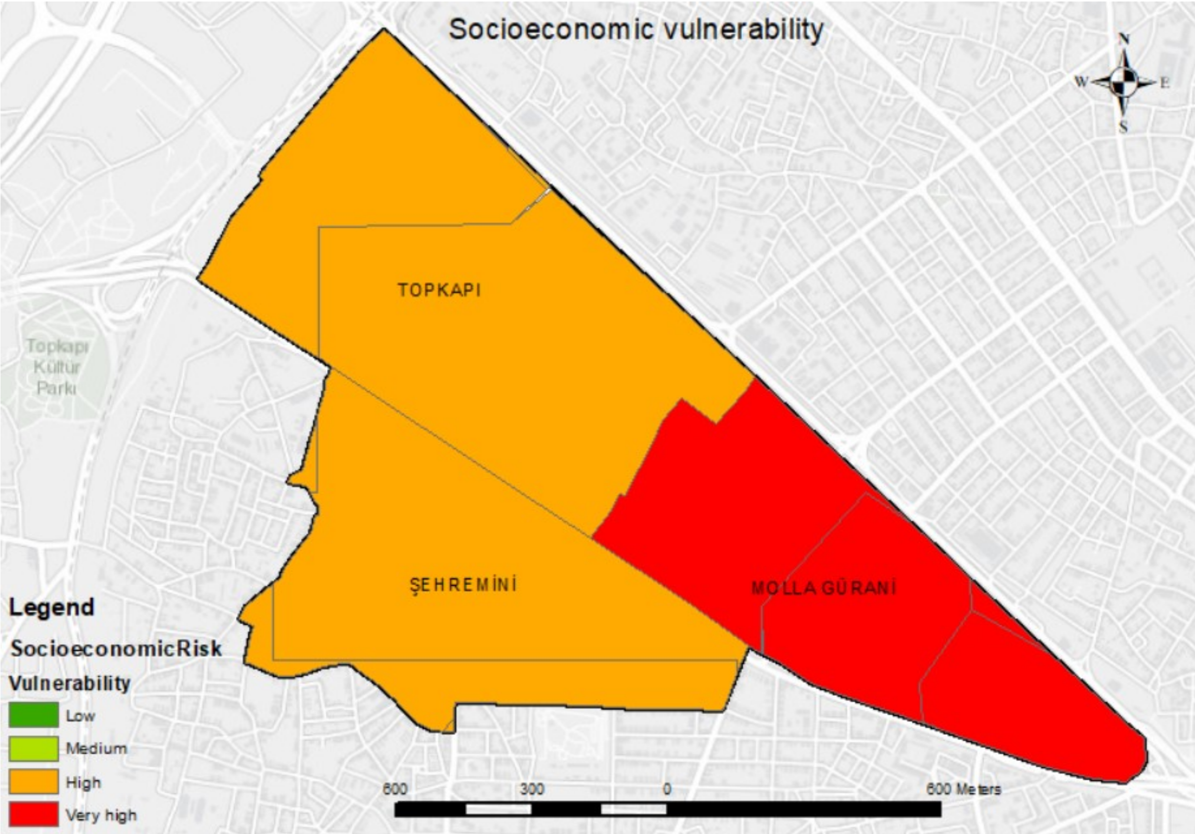


Figure 26: Socioeconomic vulnerability within the case study area. Source: Author (2022)

A similar pattern can be found when combining the vulnerability of the areas with the hazard that could occur, i.e. the earthquake and fire risk, to get the overall socioeconomic risk that exists within the case study area. Figure 27 shows the result. A significant part in Molla Gürani is shown to be at high socioeconomic risk. This can be especially attributed to the very high socioeconomic vulnerability of the neighbourhood in combination with the high risk to fire outbreaks. Next to this, a significant part of the neighbourhood Topkapi and small parts of the neighbourhood Sehremini have also shown to be at high risk. This is caused by the increased fire outbreak potential and peak ground acceleration (400-500 cm/s^2) in those areas in comparison to other parts of the case study area. Overall, it can be said that the slight difference in vulnerability, the peak ground acceleration and the fire outbreak potential between the different parts of the neighbourhoods cause the risk to shift from medium risk to high risk.

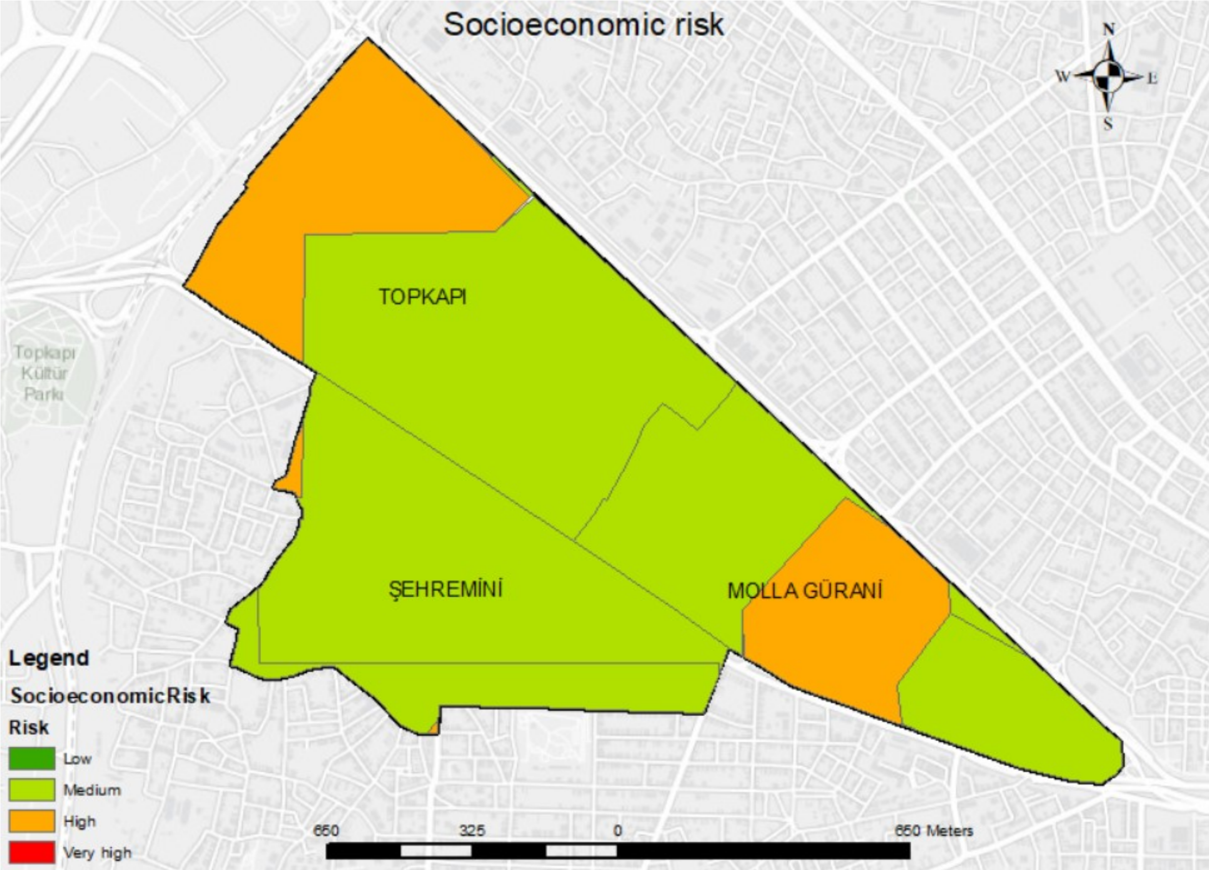


Figure 27: Socioeconomic risk within the case study area. Source: Author (2022)

Potential disruption: Traffic congestion

As described in Section 2.1, the behaviour of people is a recurring factor that contributed to the impact of the Tohoku, Kobe and Christchurch earthquakes by causing traffic jams. This can be attributed to the low understanding of evacuation plans and inappropriate behaviour of people during such earthquake events. It can be said that the unsuitable behaviour of people during an earthquake event is the result of their socioeconomic vulnerability including their risk awareness, risk preparedness, education level, etc, because this represents their knowledge on how to act and ability to act properly (e.g. elderly can be considered less mobile). With the high socioeconomic vulnerability in the neighbourhoods of the area, unfitting behaviour of people can be expected. People will want to move to open areas. However, these are very limited within the case study area. As stated by the IMM, the people are likely to move out of the dense area. According to the spokesperson of the IPA, they will move to the coasts or stay in the neighbourhoods and move around by car during an earthquake event. Consequently, it can be expected that there will be a lot of traffic on the main roads and within the neighbourhoods of the case study area. Like in the historical earthquake events of Section 2.1, this will obstruct critical services from reaching the impacted parts of the case study area. This is expected to be more significant in and around the neighbourhood Molla Gürani, because its socioeconomic vulnerability is the highest. Besides this, the increased vulnerability can be attributed to the low risk awareness and risk preparedness as mentioned before. These are assumed to be two of the main factors that contribute to unsuitable behaviour of people.

Potential disruption: Communication issues

As described in Section 2.1, the behaviour of people is also a recurring factor that contributed to the impact of the Tohoku, Kobe and Christchurch earthquakes by causing communication issues. This can be attributed to the inappropriate behaviour of people during such earthquake events. Like in the previous section, the unsuitable behaviour of people during an earthquake event can be considered the result of their low socioeconomic vulnerability. Consequently, it is likely that the people who not only live in the case study area, but also in the rest of Istanbul, will start to use the available communication networks to reach out to for example their families like happened in the historical earthquake events. As a result, it is likely that the phone services will collapse. This is also expected to be an issue according to the spokespersons of the AFAD and ITU. It will cause difficulties for the emergency services in their activities since it is likely that they will receive less information on the impacted areas from the disaster coordinating organisations like the AKOM. This might delay them in or even prevent them from operating properly.

4.2.2 Road vulnerability and Risk

By applying the additive normalisation indicator-based method to the roads in the case study area, the vulnerability of these physical elements has been determined. The results are shown in Figure 28. The main streets of the case study area (roads with a width of 9m or more) show to have low vulnerability. The reason for this is that they are made of strong material (paved with asphalt or parquet), maintained well and are significantly wide. The other streets have medium vulnerability. Like the main roads these are made of asphalt or parquet and are maintained well. Their higher vulnerability is caused by the narrow width of the streets (8m or less). As such, it is more likely that the roads become impassable when these are damaged.

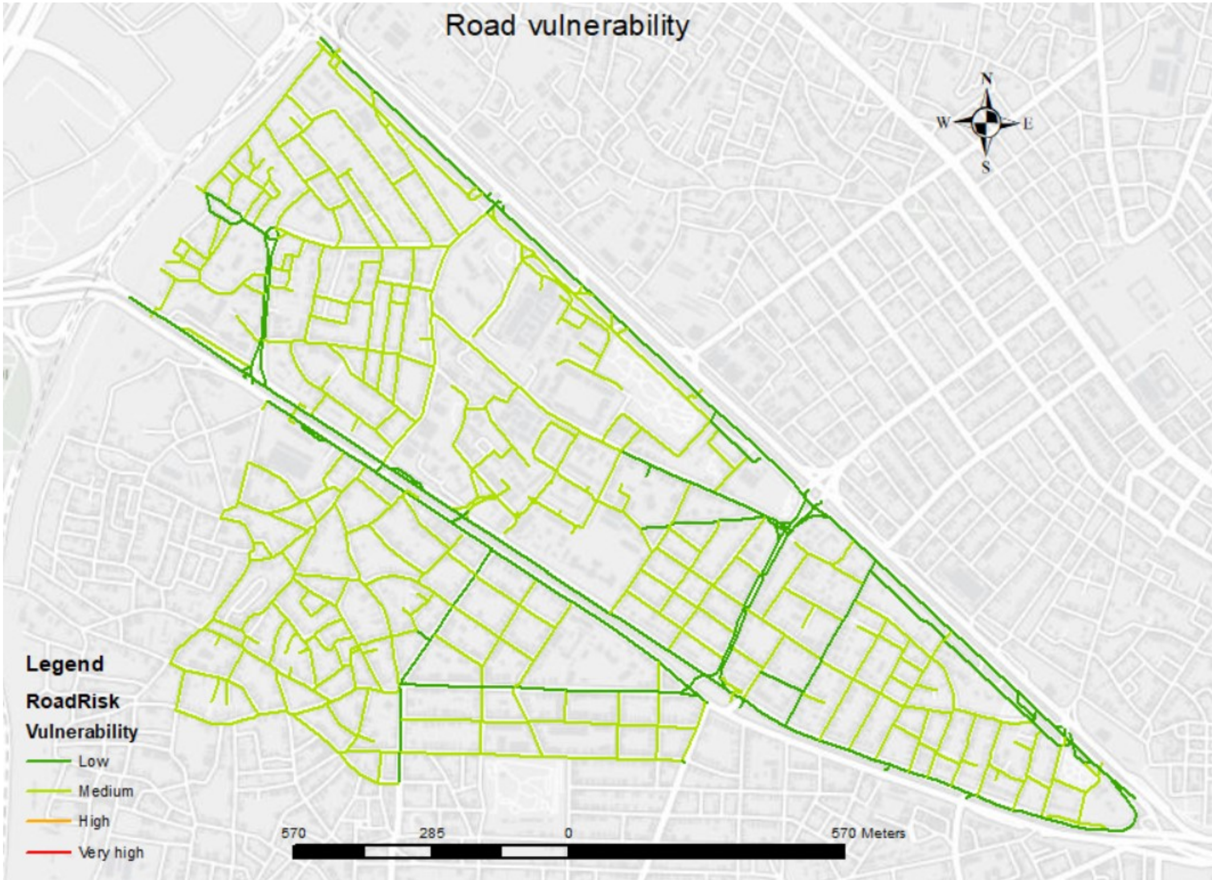


Figure 28: Road vulnerability within the case study area. Source: Author (2022)

Continuing the indicator-based method, the risk of damage to the roads in the case study area has been determined. The results are presented in Figure 29. Road damage risk is shown to be low for most part of the case study area. Roads with a width of less than 4m are at medium risk to damage. Besides this, roads with a width of 5 to 12m which are prone to higher PGA levels (400-500 cm/s^2) are at medium risk to damage. There is no high or very high risk to road damage in the case study area meaning that it is not likely that the roads become impassable due to road damage caused by the earthquake event. Thus, it is expected that road damage will not disrupt the traffic control. According to the spokesperson of the IPA this is expected, because the infrastructure is considered resilient against earthquakes.

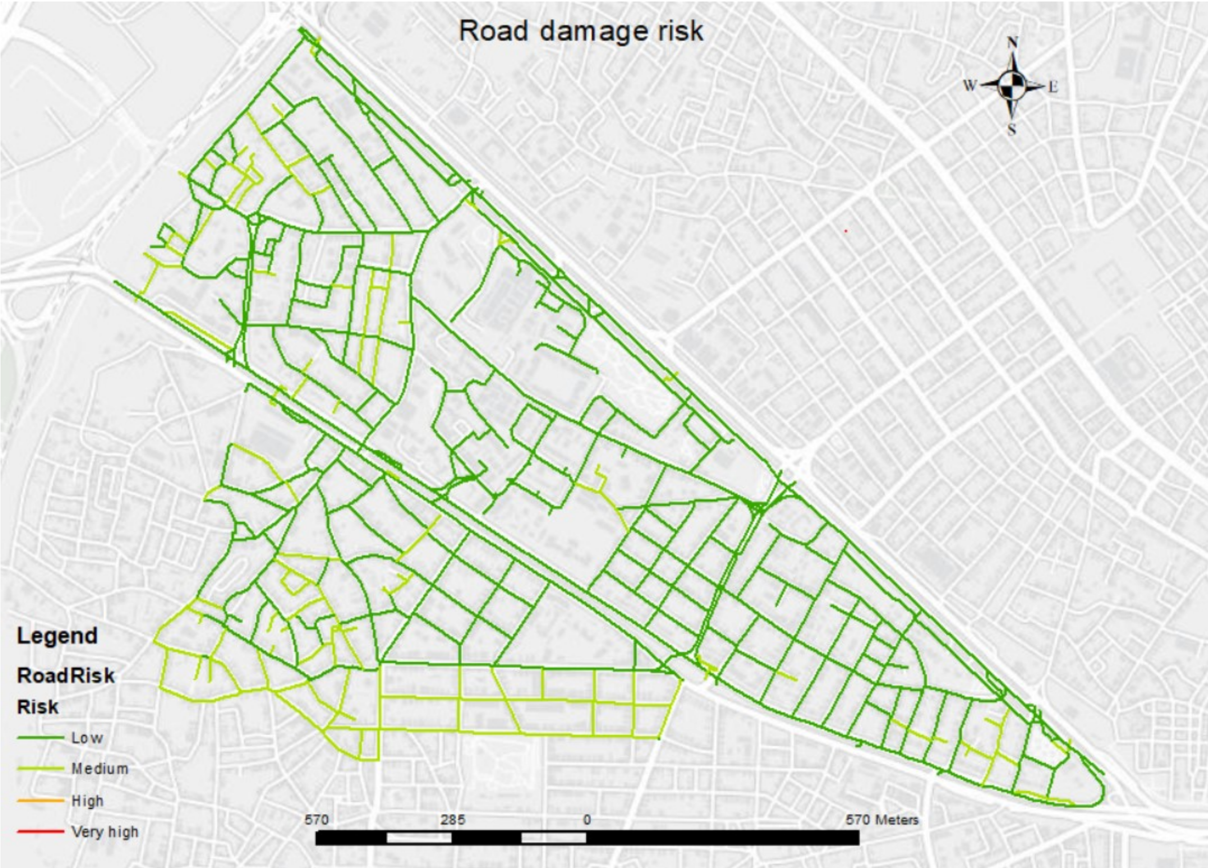


Figure 29: Road risk within the case study area. Source: Author (2022)

4.2.3 Building vulnerability and damage degrees

By applying the EMS-98 Macroseismic method as described in Section 3.4.3 to the buildings in the case study area, the physical vulnerability of the buildings according to the EMS-98 vulnerability levels as described by Milutinovic & Trendafiloski (2003) is determined. Figure 30 shows the results. Most of the buildings (76.5%) can be classified as buildings with vulnerability level B or C. This is to be expected considering the fact that the area mostly exists of low-quality dwellings as stated by Atun & Menoni (2014). Most of the buildings with vulnerability level B are located in Molla Gürani. The largest component of buildings with vulnerability level C are located in Topkapi and Sehremini. Buildings with the other vulnerability levels are scattered throughout the entire case study area. As a result, the buildings in Molla Gürani can be considered more vulnerable than in the other two neighbourhoods.

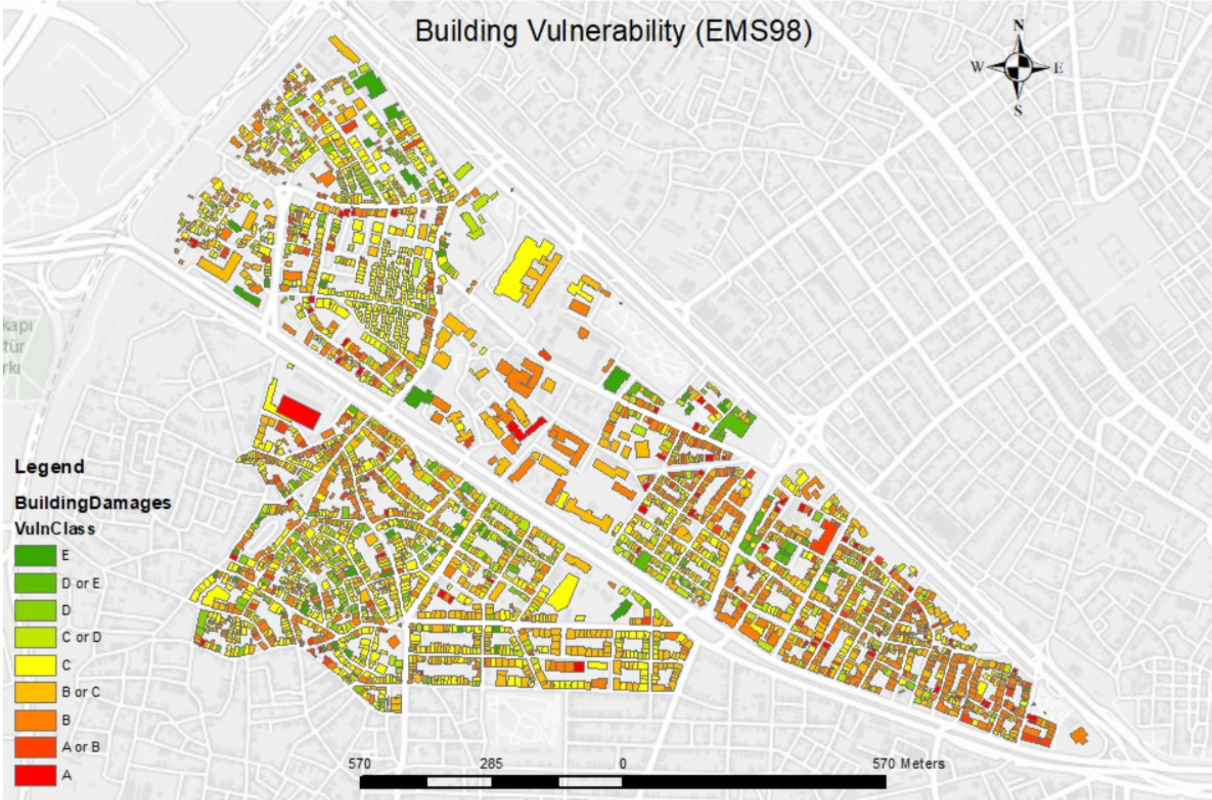


Figure 30: Building vulnerability within the case study area using the EMS-98 vulnerability classes. Source: Author (2022)

By continuing with the application of the Macroseismic method, the damage grades of the buildings in the case study area are calculated. Using Equation 6, it was determined that the earthquake event applicable to this study causes an intensity of X according to the EMS-98 Macroseismic intensity scale as presented in Table 26. Figure 31 has been created as a result. Table 15 provide the statistics of the results. Most of the buildings in the case study area show to have damage grade 3 ('substantial to heavy damage') or 4 ('very heavy damage') according to the EMS-98 damage scale after the described earthquake event. The statistics show that masonry buildings are most prone to receiving higher damage grades with 87.1% having damage grade 4 after the described earthquake event. Additionally, these buildings represent 66.0% of all the building that received damage grade 4. Reinforced concrete buildings mainly receive damage grade 3 (57.3% is classified as such). The reinforced concrete buildings that received damage grade 4 are all buildings constructed before 1980 according to low design standards. The other building typologies received damage grade 2 meaning that they are expected to receive 'moderate damage'.

Figure 32 shows the distribution of buildings with a certain damage grade in the case study area. Almost half of the buildings with damage grade 4 are located in Molla Gürani (43.8%) where also 21.8% of the buildings with damage grade 3 are located. Within the neighbourhood itself 65.4% of the buildings that are present there receive damage grade 4. In Sehremini 36.7% of the buildings with damage grade 4 are located. Here, most of the buildings with damage grade 3 are located (44.5%). Both buildings with damage grades 3 and 4 are almost equally present within the neighbourhood. The lowest number of buildings with damage grade 4 are located in Topkapi (19.4%) where 33.6% of the buildings with damage grade 3 are located. Most buildings within the neighbourhood show to receive damage grade 3 (52.0%). Based on this, it can be said that the buildings located in the neighbourhood Molla Gürani are most at risk to receiving building damage. After this neighbourhood, the buildings in Sehremini are most prone to receiving damage. Lastly, the buildings in Topkapi are shown to be slightly less prone to earthquake damage than Sehremini.

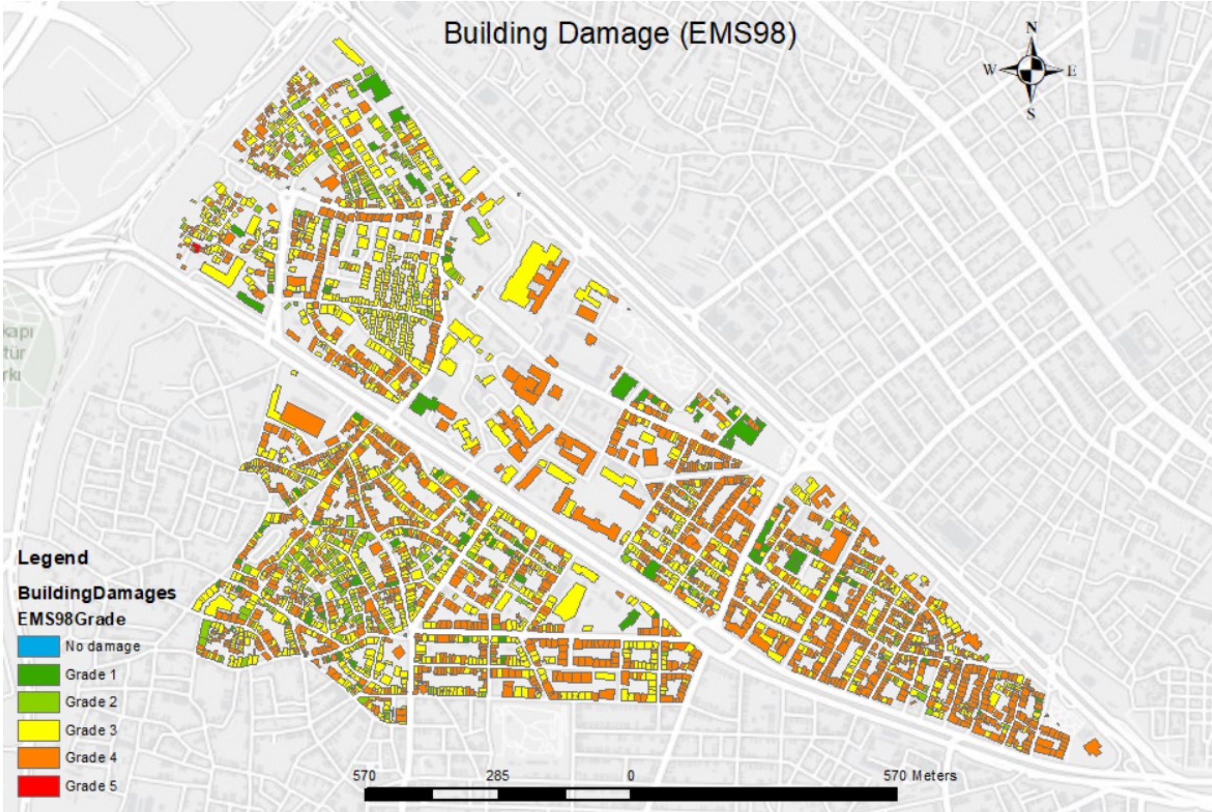


Figure 31: Building damage within the case study area using the EMS-98 damage grades. Source: Author (2022)

Table 15: The percentage and number of buildings per EMS-98 damage grade for each building typology and within each neighbourhood. Source: Author (2022)

Damage grade	No damage	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Building typology						
Reinforced concrete	0% (0)	5.6% (131)	10.8% (251)	57.3% (1334)	26.3% (613)	0% (0)
Masonry	0% (0)	0% (0)	0% (0)	12.9% (176)	87.1% (1192)	0.1% (1)
Wooden	0% (0)	0% (0)	92.3% (12)	7.7% (1)	0% (0)	0% (0)
Steel	0% (0)	0% (0)	100% (6)	0% (0)	0% (0)	0% (0)
All buildings	0% (0)	3.5% (131)	7.2% (269)	40.7% (1511)	48.6% (1805)	0.03% (1)
Neighbourhood						
Sehremini	0% (0)	4.2% (64)	8.6% (132)	43.9% (673)	43.3% (663)	0
Topkapi	0% (0)	1.9% (19)	9.9% (97)	52.0% (508)	36.0% (351)	0.1% (1)
Molla Gürani	0% (0)	4.0 (48)	3.3% (40)	27.3% (330)	65.4% (791)	0

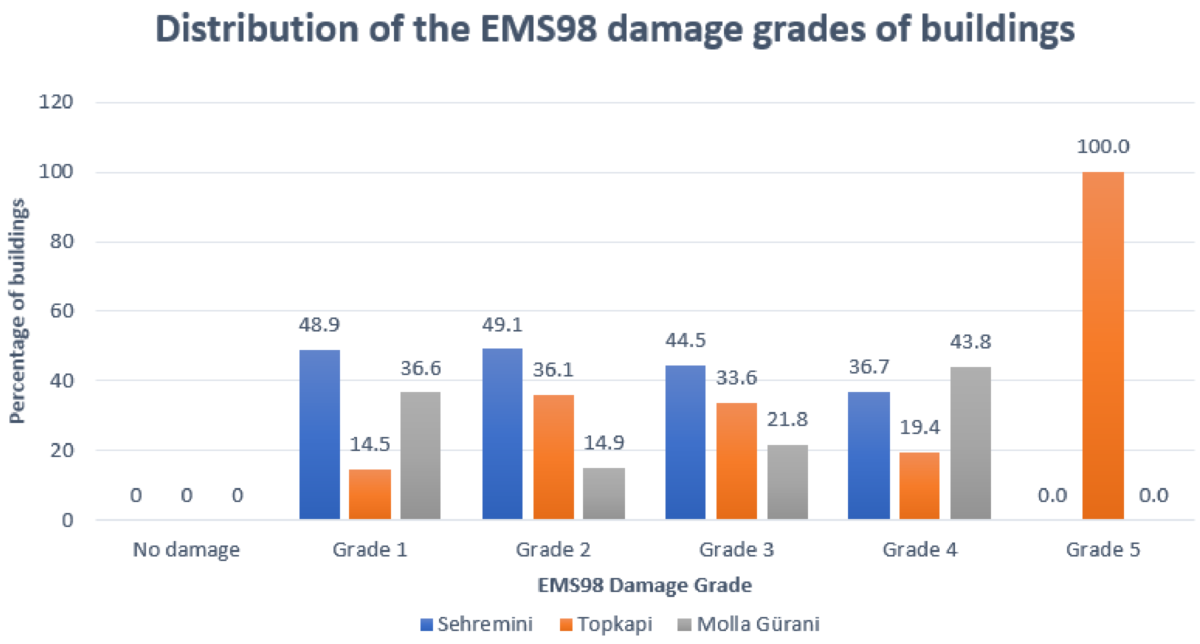


Figure 32: Distribution of the EMS-98 damage grades of the buildings within the case study area. Source: Author (2022)

Visualisation of the building damage in three dimensions together with the road risk is shown in Figure 33. Looking at the results, it immediately becomes apparent that there are relatively high buildings that are densely built and surround narrow streets which are expected to receive substantial to heavy or very heavy damage. Besides this, the identification of buildings is improved since the different buildings are recognized easier due to applying the height information than in the two-dimensional map as shown in Figure 31. Especially when zoomed-in as is done in Figure 34, the issue of having heigh, heavily damaged buildings around narrow streets, and the recognition value of the area becomes clearer. That is why it is advised to explore the 3D models further in the web scene using the link as provided in the captions of the Figures. For comparison reasons, a light blue circle is added to Figure 34 as a focus area to clearly indicate the difference with Figure 37 and Figure 38.

Figure 33: Picture of the 3D model scene showing the building damage grades and road risk for the entire case study area. The blue circle refers to the zoomed-in location in Figure 34. Link to the web scene: https://bit.ly/3KJiv7c . Source: Author (2022)

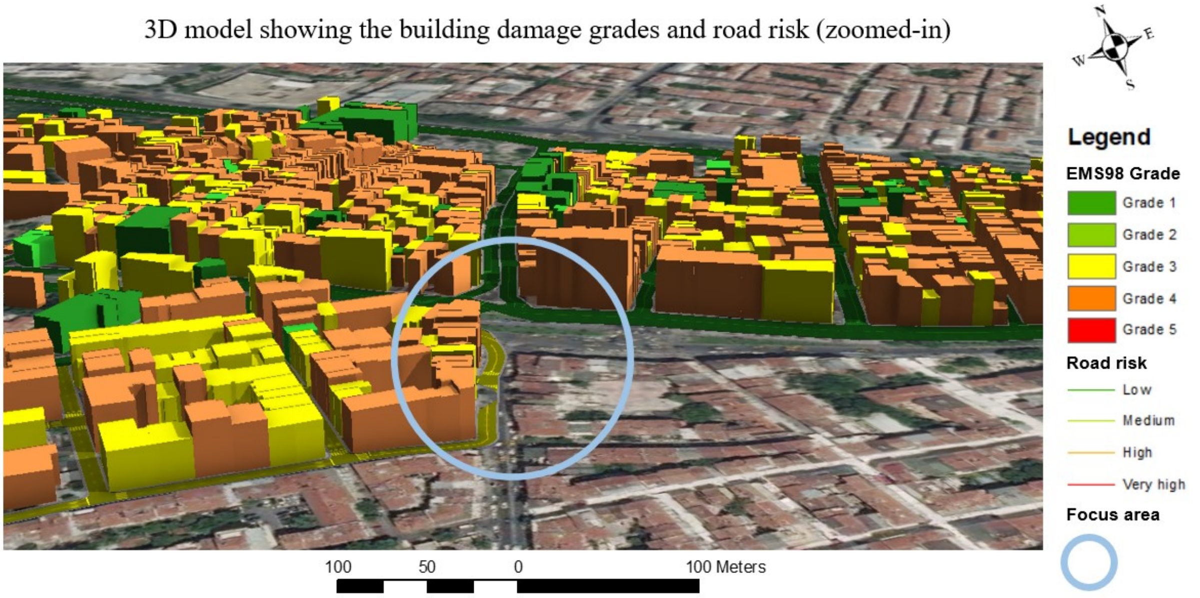


Figure 34: A zoomed-in picture of the 3D model scene showing the building damage grades and road risk. Link to the web scene: https://bit.ly/3KJiv7c . Source: Author (2022)

Potential disruption: Road closure by debris from buildings

As mentioned in Section 2.1, road blockages caused by debris from buildings and other infrastructural elements greatly disrupted the traffic control during the Tohoku, Kobe and Christchurch earthquakes. The results of the road closure analysis as described in Section 3.4.4 are presented in Figure 35. Table 16 provides the statistics of the analysis. A total of 1806 buildings with a damage grade of either 4 or 5 were included in this road closure analysis. 351 buildings have a height of 1 to 4 stories, 1438 buildings have a height of 5 to 8 stories, and 17 buildings have a height of more than 9 stories. The results after applying the method show that 29.2% of the roads are at very high risk of being closed and 14.0% of the roads are at high risk of being closed by debris from buildings. These mainly include relatively narrow roads within the neighbourhoods of the case study area that are not wider than 8m. As can be seen in the table, the largest component of roads with a width up to 4m show to be at very high risk to road closure. Similarly, the largest component of roads with a width between 5m and 8m are at low or very high risk to road closure. Wider roads are increasingly less prone to blockages, because their largest components is at low risk to road closure. The main roads within the case study area (more than 16m wide) are not in danger of being blocked by debris, because 97% has low road closure risk and the other small parts are at medium risk. Figure 35 shows that the roads located within the neighbourhood Molla Gürani are more at risk to road closures than in the other two neighbourhoods as there are more roads at very high risk. Based on this, it can be said that there is more isolation risk in Molla Gürani. The roads in Sehremini show to be less at risk. However, a significant part of the roads is at high or very high risk causing it to be likely that also Sehremini will become isolated as well. Topkapi shows to have the lowest risk to road closures. However, the locations of roads with a high or very high road closure risk could still cause the neighbourhood to become difficult to access. Thus, it can be said that especially the more narrow roads within the neighbourhoods of the case study area are prone to road closure and isolation which prevents the emergency services to provide emergency aid, while the wider roads will remain accessible for the emergency services during an earthquake event. This is as expected by the spokespersons of the AFAD, ITU and fire brigade, who thought that road blockages by debris are very likely, because there are a lot of tall, densely constructed buildings near narrow roads.

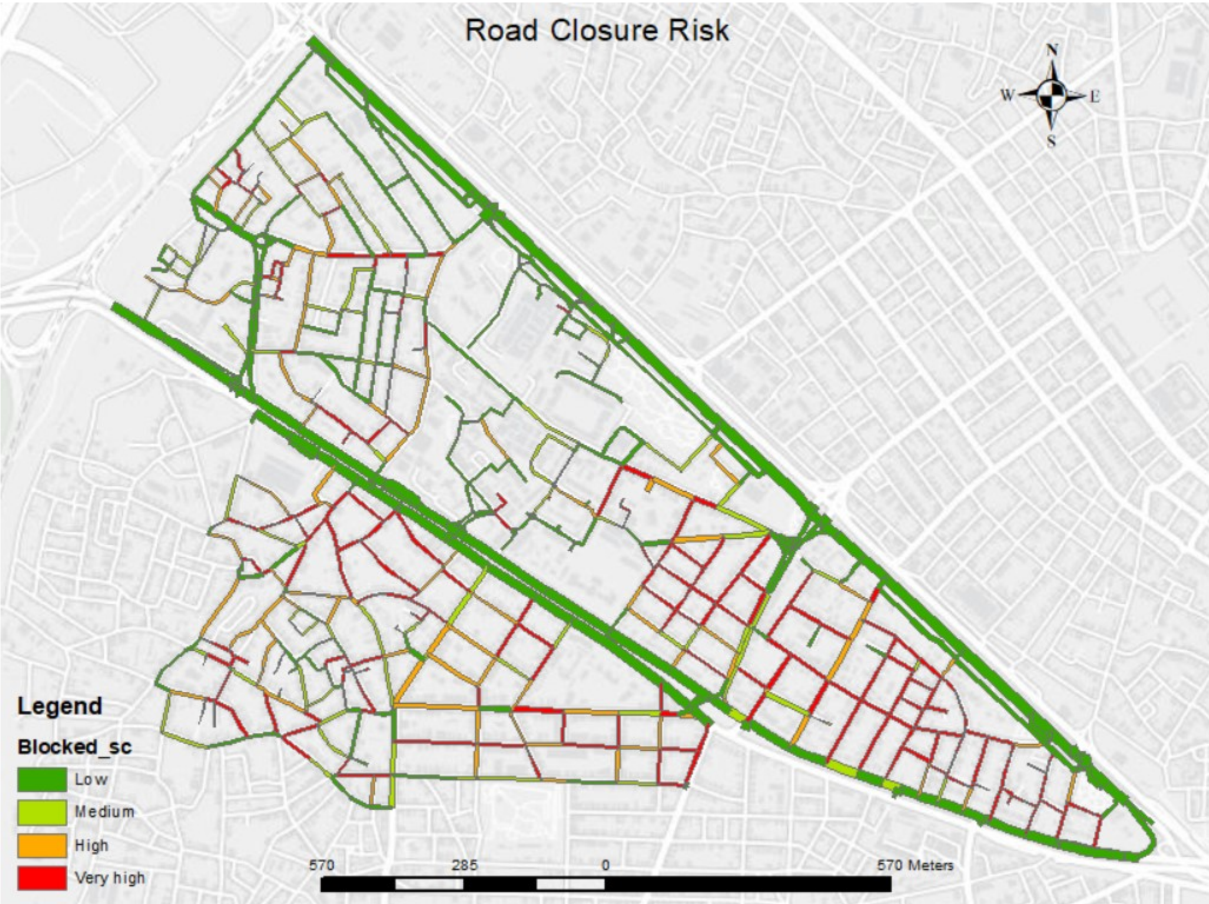


Figure 35: Road closure risk within the case study area. Source: Author (2022)

Table 16: The percentage and number of road segments with a certain road closure risk for the different widths. Source: Author (2022)

Width / Risk	0-4m	5-8m	9-12m	13-16m	>16m	All roads
Low	24.3% (26)	36.3% (152)	53.4% (31)	76.9% (30)	97.0% (97)	45.2% (327)
Medium	17.8% (19)	11.2% (47)	15.5% (9)	15.4% (6)	3.0% (3)	11.6% (84)
High	19.6% (21)	16.7% (70)	20.7% (12)	5.1% (2)	0% (0)	14.0% (101)
Very high	38.3% (41)	35.8% (150)	10.3% (6)	2.6% (1)	0% (0)	29.2% (211)

Figure 36 visualizes the 3D building models with their corresponding damage grades together with the road closure risk. It shows that the roads which are at very high risk to road closure, are usually accompanied by several densely built, 'very heavily damaged' buildings alongside the road. The road closure risk especially becomes more apparent when zooming-in on different parts of the area. Figure 37 and Figure 38 are examples. Figure 37 shows the road closure risk in a part of the case study area. It clarifies that the narrow roads surrounded by heigh, very heavily damaged buildings cause the road closure risk to be high or very high, while the major road does not show this risk, because it is much wider which prevents the road from entirely being blocked by debris. Figure 38 is added to indicate the likeliness and relative size of the debris from the buildings and with that present the cause of the high road closure risk in some parts of the area. The indicated focus area shows that the likeliness of road blockages on the major road is lower than in the narrower road. Note that the height of the debris does not represent the actual expected volume. Thus, although the risk to damage to roads is either low or medium as described in Section 4.2.2, the usage of such inner roads by emergency services can still be greatly impacted by debris from buildings. This can clearly be seen when comparing the road risk and road closure risk in the focus areas of Figure 37 and Figure 34. Again it is advised to explore the 3D models further in the web scene using the link as provided in the captions of the Figures to get a better idea on the use of 3D models.

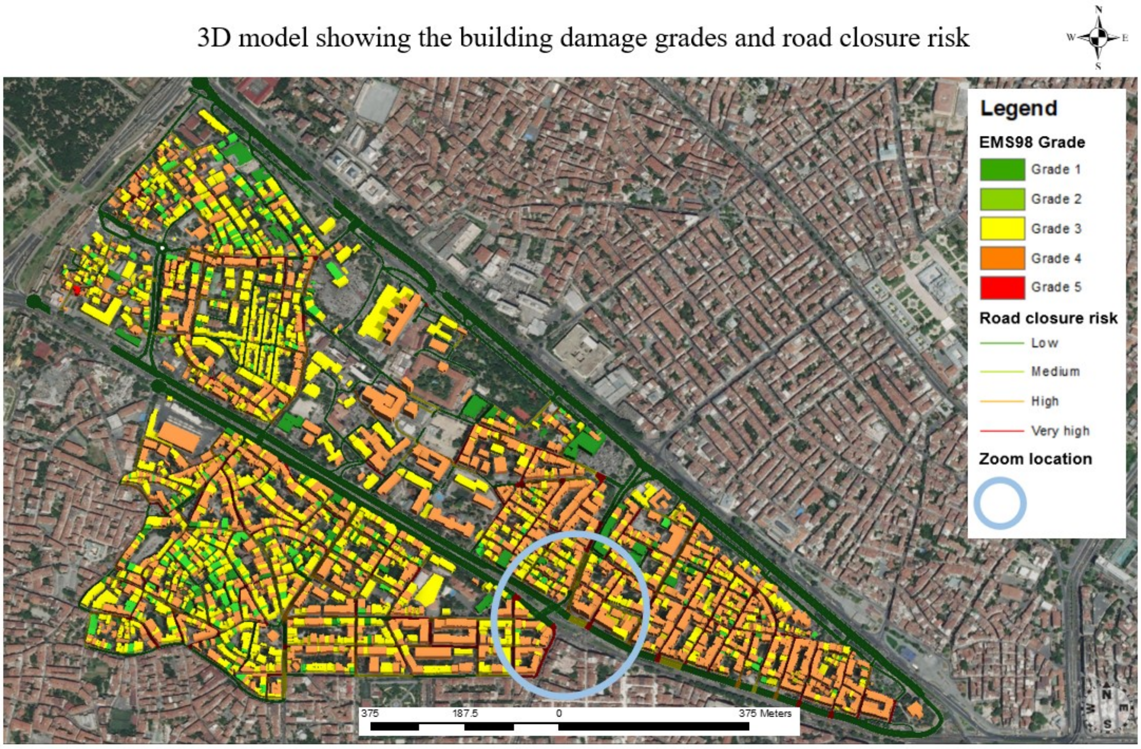


Figure 36: Picture of the 3D model scene showing the building damage grades and road closure risk for the entire case study area. Link to the web scene: https://bit.ly/3KJiv7c . Source: Author (2022)

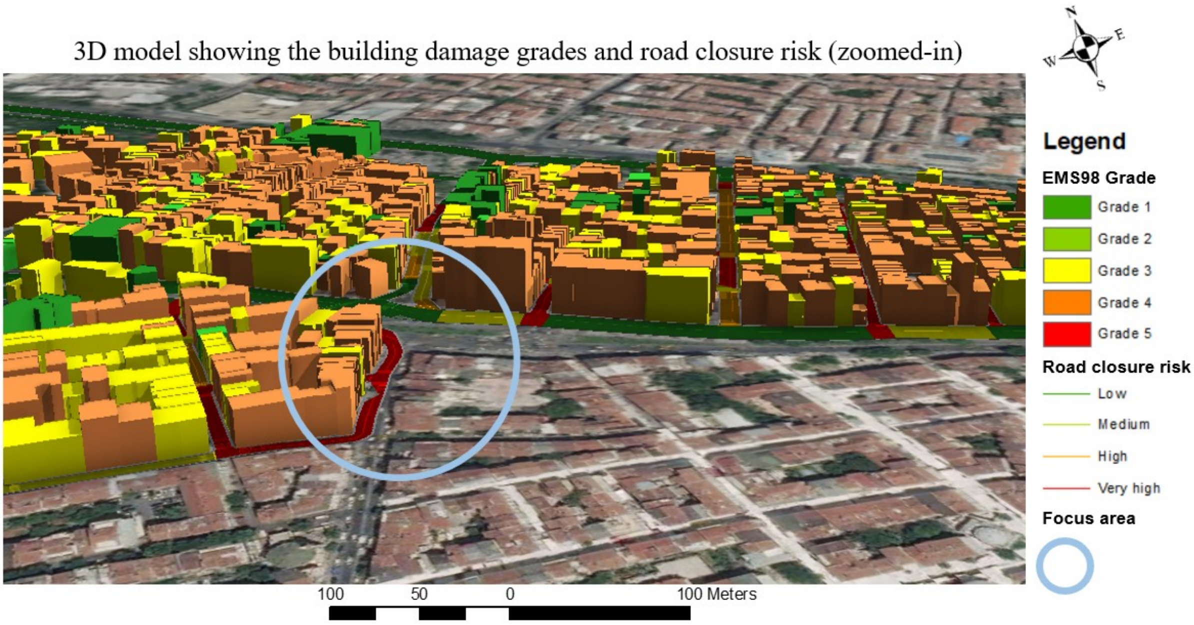


Figure 37: A zoomed-in picture of the 3D model scene showing the building damage grades and road closure risk. Link to the web scene: https://bit.ly/3KJiv7c . Source: Author (2022)

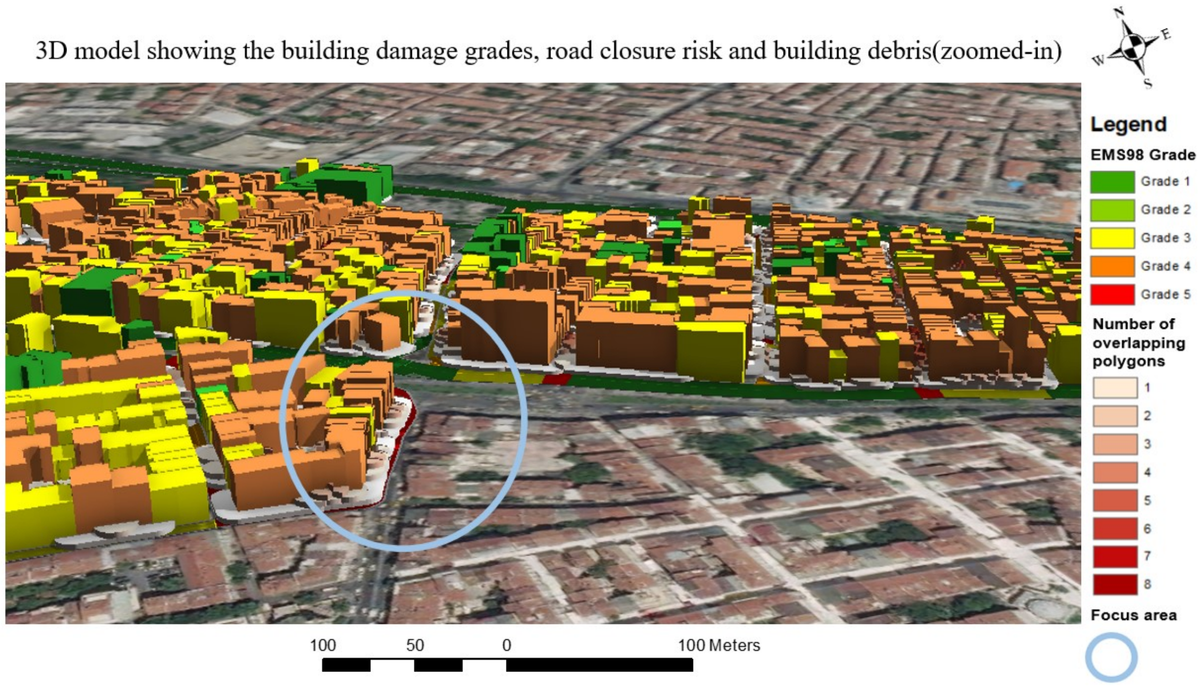


Figure 38: A zoomed-in picture of the 3D model scene showing the building damage grades, road closure risk and corresponding building debris. Link to the web scene: https://bit.ly/3KJiv7c . Source: Author (2022)

4.2.4 Systemic vulnerability and risk for the accessibility of critical services

By applying the additive normalisation indicator-based method systemic indicators, the systemic vulnerability of in the area has been determined. The results are shown in Figure 39. It shows that approximately half (49.2%) of the roads in the case study area have a medium systemic vulnerability, while the rest has low systemic vulnerability. The medium systemic vulnerability is mostly present within the inner roads of Molla Gürani and the inner roads of Sehremini in addition to some sections of main roads. Since the travel time to both the health facilities and the police within the case study area is relatively low, the shift from low to moderate systemic vulnerability can be attributed to the combination of a relatively long travel time to the fire brigades, the traffic intensity and the solid to void ratio. While the parts of the main roads with medium systemic vulnerability do not have a high solid to void ratio and travel time to fire brigades, they do have increased traffic intensity. This increases the probability for traffic jams which could make it more difficult for traffic, especially the emergency services, to quickly manoeuvre around and pass through, increasing the vulnerability. The roads with medium systemic vulnerability within the neighbourhoods do not have high traffic intensity. However, they do have a relatively high solid to void ratio and/or a relatively long travel time to the fire brigades. Consequently, these roads are more prone to becoming blocked by traffic or debris. According to the spokesperson of the fire brigade, having a lot of parked cars and traffic in those dense areas is a problem they already face in their daily activities. Besides this, the spokesperson of the fire brigade mentioned that they own trucks which can remove small debris. However, such trucks are not able to enter the inner roads of the case study area due to the urban density. These factors reduce the accessibility to an area making it more likely that it will take the emergency services, especially the fire brigade, a relatively long time to reach the impacted areas.

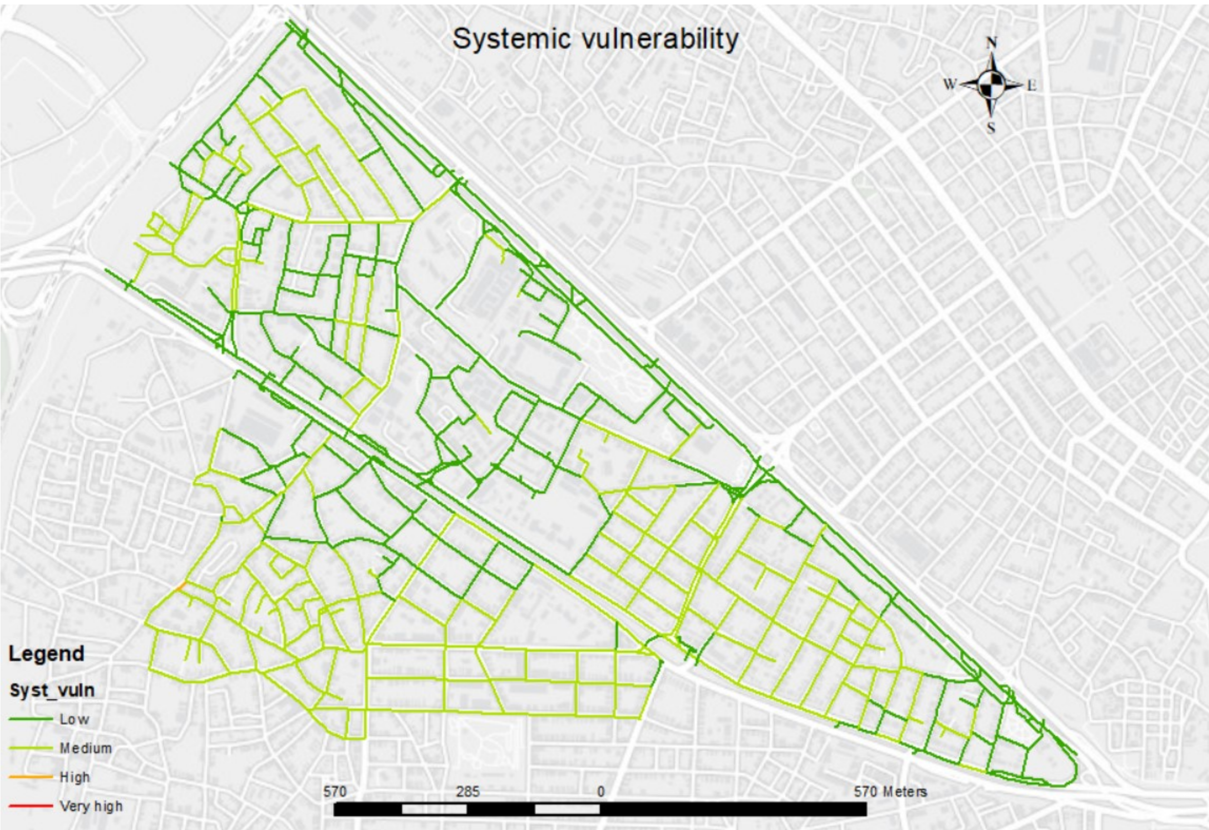


Figure 39: Systemic vulnerability within the case study area. Source: Author (2022)

Continuing the indicator-based method, the systemic risk in the case study area has been determined. The results are shown in Figure 40. Most parts within the case study area show low systemic risk with just 13.8% of the roads having medium systemic risk. Since the road risk as analysed in Section 4.2.2 is relatively low for all roads in the case study area, this does not show to contribute significantly to the increased systemic risk. What does seem to cause the shift from low to medium systemic risk are the distance to the liquefaction zones and the road closure risk due to debris from buildings. The roads that have medium systemic risk are the roads with medium systemic vulnerability that are prone to very high road closure risk or high road closure risk in combination with a relatively close distance to the liquefaction zones. These roads are mainly present in the south and southwest of the neighbourhood Sehremini and around the road in Molla Gürani that connects the two main roads of the case study area. Topkapi does not show to be at systemic risk. Based on this, it can be said that some parts within the neighbourhoods Sehremini and Molla Gürani will be relatively more difficult and with that time-consuming to reach for emergency services during an earthquake event due to the likely increased traffic and potential road blockages.

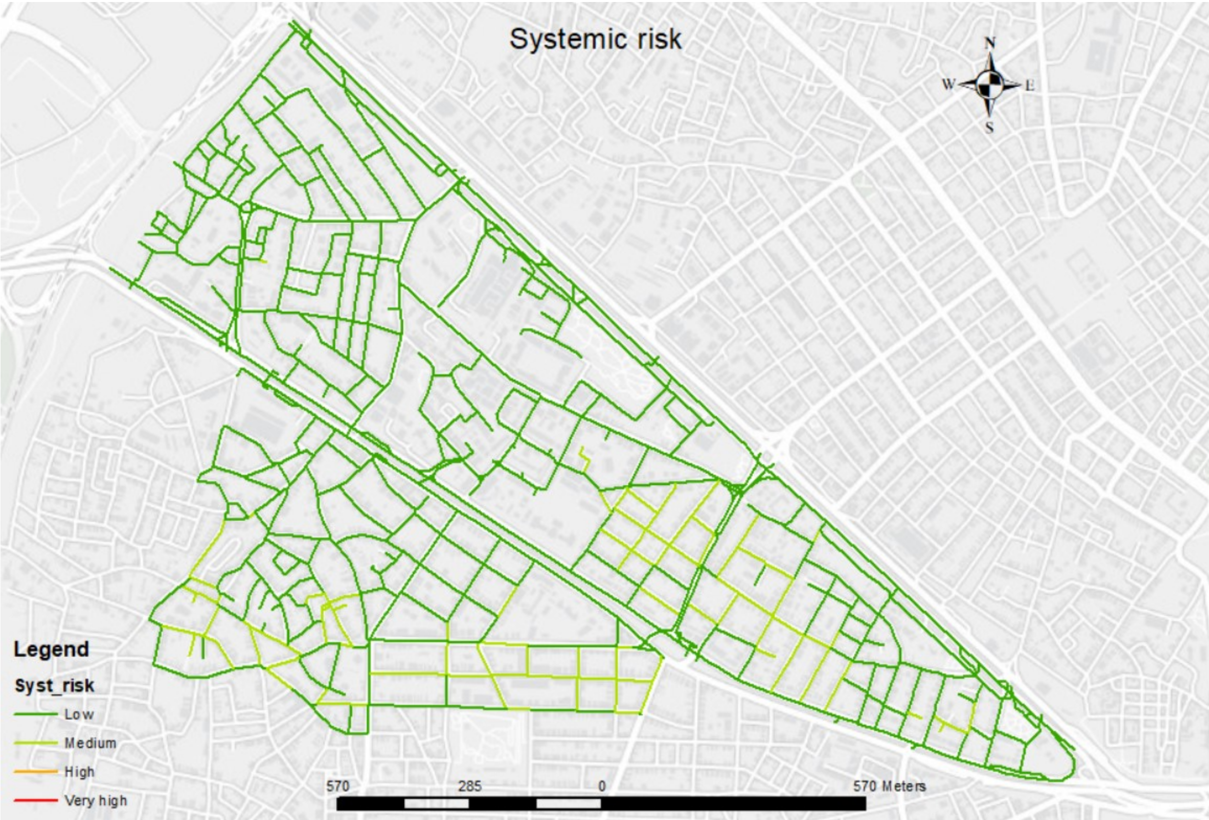


Figure 40: Systemic risk within the case study area. Source: Author (2022)

4.3 Interventions

Based on the results of the analyses in combination with the fieldwork done in Istanbul, five interventions are suggested to reduce the risk of the potential disruptions that can occur and to help to adapt to the situation after an earthquake event. The interventions have been divided in structural (Section 4.3.1) and non-structural interventions (Section 4.3.2)..

4.3.1 Structural interventions

Seismic retrofitting of the weak buildings

Damage-prone buildings in the case study are main factors that contribute to the road closure risk and systemic risk which could interfere with the traffic control in the area. As a result, it is advised to apply seismic retrofitting to such structurally weak buildings. This is important to protect the lives and assets of the building occupants and the continuity of business in the work places. Communities with more retrofitted structures can recover from earthquakes more rapidly. When living in retrofitted buildings you are less likely to be injured, because there is lower risk that the buildings will collapse or be heavily damaged. Also, you are more likely to still have a home or job to which you can go to. Business in retrofitted buildings are more likely to be able to quickly continue their work and have fewer resource losses (FEMA, 2022). Having such structurally stronger buildings also reduces the risk of debris to occur which reduces the road closure risk. This way, the areas within the neighbourhoods of the case study area should remain more accessible for emergency services.

It has to be noted that not all weak buildings within the case study area can be reinforced, because of two main reasons. The first reason is that there are listed cultural heritage buildings within the case study area according to the IPA. Such buildings are not allowed to be rebuild. The second reason is that the people who live within the buildings are low-income newcomers who do not have a lot of money for the reinforcement of the buildings as mentioned by the spokespersons of the AFAD, IPA and Fatih Municipality. Based on these two reasons, a limited number of buildings which are located in building blocks without any listed buildings can be seismically retrofitted. Due to missing data on the exact location of these listed buildings, such buildings are assumed to be the buildings classified as cultural facilities, religious facilities or tourism facilities in the dataset 'Fatih_poi'. By analysing the location of buildings with damage grade 4, road closure risk and systemic risk, the buildings for reinforcement have been prioritized. The results are shown in Figure 41.

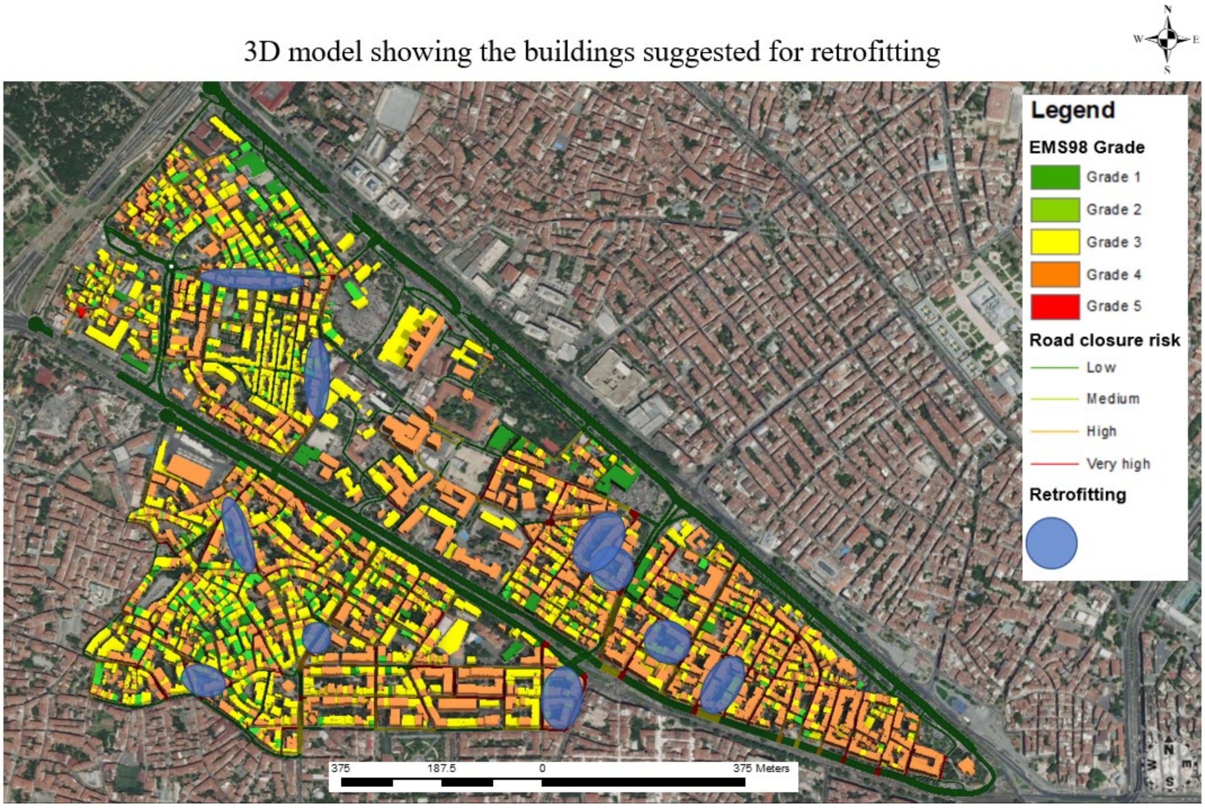


Figure 41: 3D models showing the buildings suggested for retrofitting. Source: Author (2022)

There are several ways which can be used to reinforce buildings. The main options considered applicable to the case study area are listed below.

- Applying stiff, strong and ductile structural elements in strategic locations to improve structural configuration and protect existing elements (particularly columns) from the effects of excessive lateral displacement (Hopkins et al., 2006).
- Jacketing of key columns and beams with reinforced concrete to improve their load-carrying capacity and to make up for inadequate toughness and ductility (Hopkins et al., 2006; JICA & IMM, 2002).
- Applying reinforced concrete walls on the basement floor of the building (Bogazici Univerisity et al., 2003; JICA & IMM, 2002).
- Applying base isolation which decreases the period and the effective damping (Bogazici Univerisity et al., 2003).
- Placement of energy damping systems which damp the earthquake effects and decrease the displacement demand of the structure (Bogazici Univerisity et al., 2003).

Local gathering facilities for spontaneous rescue teams

Directly after an earthquake event it is important to quickly execute search and rescue activities and provide emergency aid to reduce the number of casualties. Here time is crucial. According to National Research Council (1991), major disasters have shown that both resources for volunteers and the potential for logistical issues are important. Spontaneous volunteers are invaluable during the emergency response, because during the first hours after a disaster, bystanders make the majority of the rescues and volunteers and citizens are often active in clean-up activities. However, it is difficult to have the essential resources ready when they are most needed. Therefore, in order to aid the emergency services and volunteers in their activities and with that help them to reach the casualties as quickly as possible, it is suggested to assign locations within the case study area which can host the gathering of the involved volunteers to make it more easy to coordinate the rescue and clean-up activities and which can store resources that are helpful in for example removing debris from the roads and reaching and aiding the people in need. Stocking such resources is also a necessary measure suggested by Ranghieri & Ishiwatari (2014) based on the Tohoku earthquake that happened in 2011. According to the spokesperson of the AKOM, such 'equipment containers' do already exist around Istanbul. This study suggest additional locations specifically for the case study area. To mention a few resources that could be stored in such locations:

- Tools and other resources which can be used to remove debris and open the streets to give access to the emergency services.
- The spokesperson of the AKOM mentioned the satellite phones. These can be useful especially when the communication networks collapse due to the overuse of the networks by the locals to restore the communication between the disaster response units..
- The spokesperson of the IMM mentioned speakers. They can be used to control a large group of people and reduce the panic. Besides this, they can be used to coordinate the volunteers which aid in the response activities.
- Portable generators which can be useful when power goes down during an earthquake. Power (and other lifelines) are essential during the response and recovery phases (National Research Council, 1991).
- Fuel for the emergency and transportation vehicles which can be useful in the event that it becomes scarce (Ranghieri & Ishiwatari, 2014).
- Food and water.
- Medical aid kits.

Next to this, since it is likely that several areas will become difficult to reach as discussed in Sections 4.2.3 and 4.2.4, placing fire hydrants on critical locations is considered important to aid the fire brigade in fighting the potential fires that might occur. The additional gathering facilities and fire hydrant locations within the case study area as suggested are shown in Figure 42. The locations of the gathering facilities include both existing buildings that are not prone to being damaged, and small open spaces which are thought to have available space based on the fieldwork. These locations will remain accessible during the earthquake event since there is low road closure risk and systemic risk surrounding the places. The locations of the fire hydrants are located in areas which have shown to become isolated due to road blockages. Therefore, large fire trucks are not able to reach such areas. Moreover, in these areas a significant number of heavily damaged buildings are located. Heavy damage is assumed to be a source of ignition.

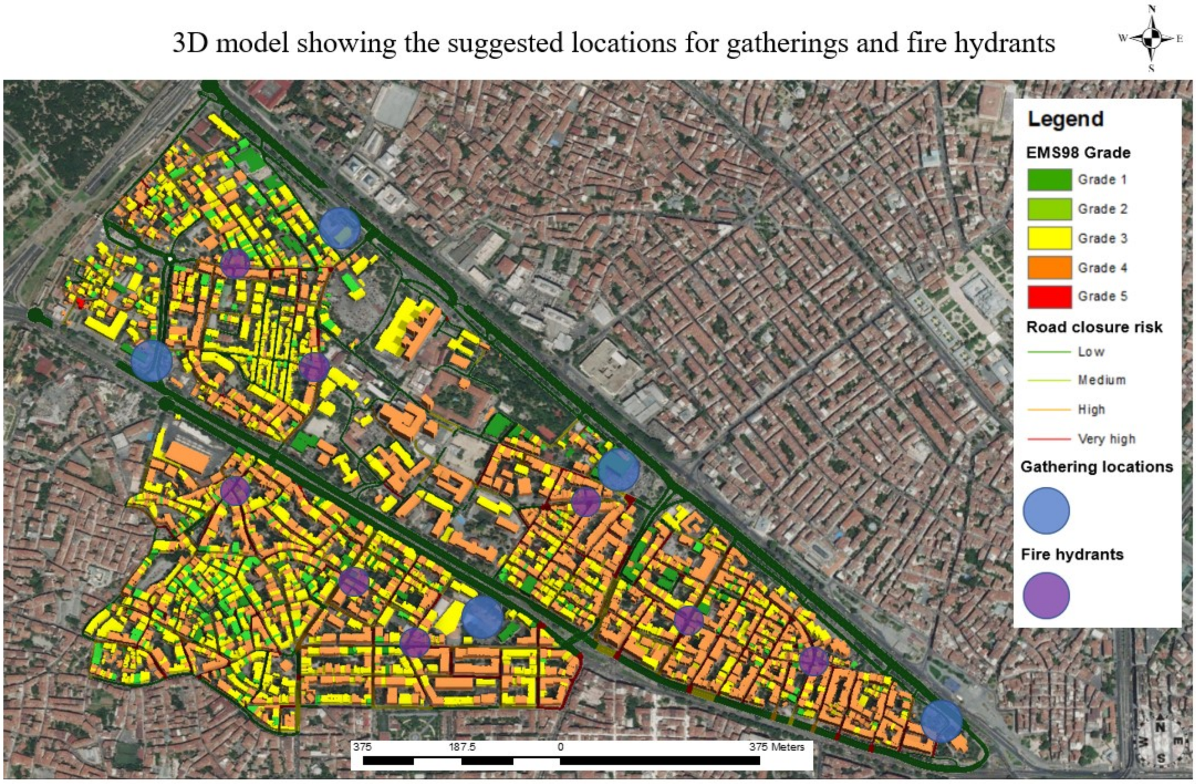


Figure 42: 3D models showing the suggested locations for gathering facilities and fire hydrants. Source: Author (2022)

4.3.2 Non-structural interventions

Raising awareness

As described in Section 4.2, the socioeconomic vulnerability of the neighbourhoods is high to very high. The higher vulnerability of Molla Gürani can be rooted to its lower risk preparedness and risk awareness. Therefore, it is important to raise awareness and educate the people in the area, especially in Molla Gürani, on the risk that exists for them to earthquakes and on how they can prepare for it.

Educating people is an important task mentioned by the spokesperson of AFAD. It can be done through several activities. Booklets can be distributed among the community introducing them to different topics related to earthquake awareness and preparedness. Besides this, the media can be used to spread the word about the importance of being aware about the earthquake risk. Next to this, the public should be actively involved. This can be done with recurring, interactive, participatory education sessions in which the participant are engaged in discussion and collaborative activities to explore the earthquake risk related topics and reflect on the issues that exists and their own personal experiences. Another option is to have earthquake safety exhibitions Such demonstration projects increase the visibility of natural hazard reduction and can help to improve government, industry, and public participation in preparedness activities (National Research Council, 1991).

These education activities should cover all phases of disasters, the mitigation, preparedness, response and recovery phases. That is why topics such as explanation of the disasters, risk preparedness, and what to do and not to do during disasters need to be covered. Besides this, it is important to educate the community on topics covering the disaster legislation such as insurance possibilities and the building codes. On top of that, it is important to teach the community on essential skills needed for preparedness (e.g. stabilizing furniture, finding safe places, etc.), for the response phase of the earthquakes (e.g. first aid, search and rescue, etc.), and for healthy living during temporary relocation. This can especially be done during the beforementioned interactive education sessions. The suggestions on how to raise awareness are based on those suggested by Bogazici Univerisity et al. (2003) and Jimee et al. (2012).

Offering incentives to the ones who need it most

Increasing the risk preparedness of the community can be done by the general public themselves. They can act and implement measures within their own homes that make them more prepared and reduce the impact of the earthquakes (e.g. emergency resources, stabilizing furniture and structural measures). However, often people do not have enough money nor the luxury of spending their money on risk mitigation measures. According to the academic of the ITU, the people in the area have other problems as well such as illnesses or their economic conditions. These are usually prioritized. Therefore, it is suggested to offer incentives by for example the government to the households in the case study area that require them the most. This way, these people can still acquire earthquake preparation measures to make themselves more resilient.

It is expected that the households which would benefit most from the incentives are mostly located in Topkapi where, according to Table 14, live most of the people who are considered to have a low-income, or in Molla Gürani where most buildings with damage grade 4 are located. People who live in a building that is at lower risk of collapse or heavy damage are thought to have a lower need of being prepared to earthquakes. That is why the aided households should live in a building that is classified as having damage grade 4 or higher.

Promote the use of micro-mobility

As suggested by the IMM, promoting the use of micro-mobility could be one of the measures that will reduce the traffic intensity within the case study area. Consequently, traffic congestions could become less apparent which should increase the accessibility of the case study area also during earthquake events. According to Møller et al. (2020), the implementation of micro-mobility are increasingly adopted in car-centred cities in Europe, America and Asia. E-scooters in particular are growing in popularity at an incredible rate, with already more than 20 million users in Europe alone. They can serve as a catalyst toward shared and low-carbon mobility by improving access to public transport and by supporting a change in urban mobility habits reducing taxi and car trips in cities. When it improves the access to public transport and replaces taxis and private cars, it will decrease pollution, noise and congestions, while using the already scarce urban space in the case study area more efficiently. Surveys done by the micro-mobility organisation Voi show that 63% of their users combine e-scooters with public transport. Already 12% of the e-scooter trips are replacing cars, taxis and ride hailing services. Besides this, it is increasingly being used for commuting purposes instead of leisure. Lastly, the latest innovation, swappable battery scooters, has shown to reduce emissions by 51%. Eventually, introducing micro-mobility helps in cities reaching their climate goals, reclaims space and improves the quality of life.

In order to be able to implement such micro-mobility services, it is important that cities and policy makers invest in effective policies, micro-mobility infrastructure (i.e. parking spots and safe infrastructure), innovation and responsible business practices. This also applies to the case study area. Policies can include requirements, such as safety, sustainability, operations, data-sharing, and limits for the number of micro-mobility service providers which should promote responsible and sustainable practices. Besides this, policies can be used to set national traffic and product requirements, and for the allocation of parking spaces. According to Møller et al. (2020), e-scooters can be used by 8 to 10 people per day and 10 to 15 e-scooters can be placed in one car parking spot, while cars can transport 1.3 people and are parked for 95% of the time. Contributing to this, Incentivized Parking Zones as used by Voi can be implemented which encourage people to park in the designated area with ride discounts. It is suggested to focus on creating parking spaces within the inner roads of the neighbourhoods of the case study area where many cars are parked. Therefore, a lot can be gained in terms of parking space for the e-scooters by converting the remaining empty spaces and the car parking spots, and accessibility by increasing the width of the passageway. Additionally, traffic calming measures (e.g. speed bumps) and separation of cars and the micro-mobility could contribute to safety. Lastly, public-private partnerships between public transport and micro-mobility should be promoted to support the transition.

5 Discussion and Conclusion

In this chapter, first the research questions as defined in Section 1.6 are answered and discussed separately in Section 5.1 to provide a clear overview of what has been achieved. After this, in Section 5.2 a summary of the entire study is provided. Lastly, in Section 5.3 a variety of limitations that are present in this study are described. Based on this, it suggests directions for future research that could aid in improving the vulnerability and risk analyses, the determination of potential disruptions, the application of 3D modelling and the suggesting of suitable interventions

5.1 Answers to the research questions

Research Question (RQ) 1.1 What are disruptions from earthquakes seen in other metropolitan areas around the world that impact the traffic control?

In Section 2.1, the Tohoku, Kobe and Christchurch earthquakes are analysed to identify such disruptions from earthquakes. A short description of each event in provided in the boxes below. The main recurring disruptions that impacted the traffic control during the three analysed earthquake events were: damage to or deformation of the roads and bridges, road closure due to debris from buildings and other infrastructural elements, traffic congestion and communication issues between disaster management organisations due to an overload of the communication systems. Besides this, the loss of other transportation systems, such as the public transport and ports, and lack of available resources, such as gasoline and aid materials, seem to have impacted the traffic control.

<u>Tohoku Earthquake</u>

During the Tohoku earthquake in 2011, widespread damage to buildings and roads, blocked roads by mud and debris and concerns about radiation made several areas inaccessible for emergency services. In addition, lack of gasoline made transportation more difficult. Human behaviour caused an increase in the use of the communication network, causing communication issues which made disaster coordination more difficult. Besides this, people started to move around by car which caused traffic congestions that obstructed the emergency services.

<u>Kobe Earthquake</u>

The Kobe earthquake in 1995 saw a lot of damage due to the city not having the right design standard for the structures. Major expressways that connected Kobe with other parts of the country became unusable. Consequently, Kobe's transportation system was at less than 5% of its normal capacity. Besides this, it meant that important access routes for emergency services and for the transportation of goods to the impacted areas were lost. Contributing to this were the blockages on many narrow roads caused by debris and other infrastructural elements such as low-hanging power lines and broken water pipes. Besides this, human behaviour contributed to a large number of abandoned cars and people leaving the city, causing traffic congestion which obstructed the emergency services.

<u>Christchurch Earthquake</u>

During the Christchurch earthquake in 2011, extensive damage to the road networks, bridges and tunnels, especially caused by liquefaction, in combination with road blockages due to rock falls greatly obstructed the transportation of goods as routes became restricted and impassable. Contributing to this, was the evacuation of people from major buildings. This behaviour caused traffic jams throughout the city. Such congestions remained an issue for months.

To discuss these results, additional examples of earthquake events were analysed. This included the Izmit earthquake that happened in 1999 and hit an industrial and populated area in Turkey as described by JICA & IMM (2002), and the Haiti earthquake that happened in 2010 and affected the capital Port-au-Prince causing great damage as described by Pallardy (2022). It was found that this study identified the most common disruptions, because the aforementioned studies also highlighted the impact of road blockages, traffic congestions and lack of resources on the traffic control. However, additional disruptions were identified as well, including failure of telecommunication cables and power systems, untrained personnel and loss of critical facilities such as the hospitals. Having additional insights on disruptions and their corresponding impact on traffic control can provide additional directions for the analysis on potential disruptions in the case study area.

RQ 1.2 What potential disruptions are applicable to the case study area?

Based on the literature study on the historical examples as described in Section 2.1 in combination with the known local characteristics of the case study area as described in Section 1.5, it has been identified that the area is likely to be prone to damage to the road network. Besides this, due to the weak, densely constructed building stock that is present, it is likely that narrow roads will be blocked with debris from the buildings and other infrastructural elements. Fatih is also known to have a lot of traffic, many low-income newcomers and tourists who are expected to have low risk awareness and preparedness, and many businesses. Thus, as happened during the Christchurch earthquake, it is likely that there are many people, especially during the day, who will evacuate or go home in a chaotic manner which could cause traffic congestions. Contributing to this, are the major hospitals that are located in or near the area which will attract many people. Lastly, it is likely that the behaviour of people will cause the communication networks to be overloaded, which could cause communication issues for the disaster management bodies and emergency services like happened during the Tohoku earthquake in 2011.

As discussed in the previous research question, it is possible that there are other disruptions which were not identified during the analysis of the historical earthquake events. As such, it could be that there additional potential disruptions, such as the loss of the power system, which can occur and affect the traffic control in the area. However, the used potential disruptions were the main expected disruptions by the interviewed people during the fieldwork.

RQ 2.1 What vulnerability indicators can be used?

As described in Section 3.4.1, this study distinguished between socioeconomic, road, building and systemic vulnerability indicators. For socioeconomic vulnerability, the indicators risk awareness, risk preparedness, the percentage of low-education levels, the percentage of low-income level, the percentage of people over 65 years old and the population density were used. Road vulnerability included road width, road type and road maintenance level. Building vulnerability included building typology, building age, building height, the difference in building height between adjacent buildings, the position of the building in a building block and the use of the building. Systemic vulnerability included travel time to health facilities, travel time to emergency services, solid to void ratio and traffic intensity.

The indicators as applied in this study were selected based on an extensive literature study on earthquake vulnerability indicators, in combination with their applicability to the case study area considering the local characteristics and the data availability. In literature a wider variety of vulnerability indicators can be found. For example, there are more behaviour modifier factors of buildings presented in literature (Appendix B) which were excluded, because the data was not available. This include the factors: state of preservation, structural system, roof, retrofitting intervention, plan irregularity, superimposed floors and foundation. Applying these indicator is expected to increase the vulnerability and damage grades of especially the older, not retrofitted buildings which are likely to be less strong and more deteriorated. Besides this, El-Maissi et al. (2020) stated that the soil type and geometrical characteristics such as the height of embankments, compaction quality and slope angles are additional indicators that can be used to determine road vulnerability. These could cause the road vulnerability and risk in the case study area to become more heterogenous.

RQ 2.2 What parts of the case study area are most vulnerable?

The results as described in Section 4.2 show that the entire case study area is socioeconomically vulnerable to earthquakes. A difference in risk awareness and preparedness causes the neighbourhood Molla Gürani to have the highest socioeconomic vulnerability (see Figure 26). It is imaginable that the socioeconomic vulnerability could be even higher during the day. According to the spokesperson of the IMM, there are many additional people during the day including tourists and immigrants. This increases the population density and could reduce the risk awareness and preparedness.

The roads in the entire case study area are not vulnerable to damage, because Figure 28 shows that the roads have either low or medium vulnerability. As the same road material and road maintenance level were applied, the difference in vulnerability is only caused by the difference in width. That is why roads with a width over 9m have low vulnerability, and all the other roads to have medium vulnerability.

In contrast, the buildings are vulnerable to damage. Most buildings are categorized as class B or C according to the EMS-98 vulnerability levels. This is mainly caused by the construction type and age (applied design codes) of the buildings. Figure 30 shows that most buildings with class B are located in Molla Gürani, making this the area with the highest physical vulnerability.

As a consequence of these results, it has been determined that the systemic vulnerability in the case study area is not high (see Figure 39). Approximately half of the roads in the area have medium systemic vulnerability. These are mostly present within the inner roads of Molla Gürani and the inner roads of Sehremini which have a relatively long travel time to the fire brigades and high solid to void ratio, in addition to some sections of the main roads which have relatively high traffic intensity.

The results on the socioeconomic vulnerability can be evaluated by comparing them to the results of the survey work from Ugur et al. (2018). The social vulnerability as determined by Ugur et al. (2018) similarly shows that Molla Gürani with a social vulnerability score of 52.39 has a higher social vulnerability than Topkapi and Sehremini which both have a similar, lower social vulnerability score of 45.13 and 44.32, respectively. Besides this, in comparison with Fatih and the entire Istanbul, which have an average score of 50.79 and 50.00 respectively, Molla Gürani shows to have higher socioeconomic vulnerability, while Topkapi and Sehremini remain somewhat below both averages. Ugur et al. (2018) classified Fatih as one of the mid-upper vulnerable counties of Istanbul where the socioeconomic characteristics of the area contributed most to the social vulnerability of the district. Based on this, it can be said that the socioeconomic vulnerability as determined by this study is realistic.

As discussed in the previous research question, other vulnerability indicators could have been applied to the vulnerability assessments. Besides this, proxies were used for some building vulnerability indicators. The building codes were estimated by building age, and the vertical irregularity was estimated by the building use. Besides this, the Macroseismic approach distinguishes between buildings that are located in the middle and on the corners of a building block. In this study, all these buildings are considered ‘middle’ buildings, because there is no efficient way to distinguish between them. This might have affected the most socioeconomic, road, building and systemic vulnerable locations as presented in Sections 4.2.1, 4.2.2, 4.2.3 and 4.2.4.

RQ 2.3 What parts of the case study area are more at risk?

The results as described in Section 4.2 show that the socioeconomic risk in the case study area is either medium or high. Figure 27 shows that a significant area within Molla Gürani has high socioeconomic risk, caused by the very high socioeconomic vulnerability in combination with the high fire outbreak potential. Other areas include, the west of Topkapi and small parts of Sehremini. This is caused by the relatively high fire outbreak potential and PGA levels (400-500 cm/s^2) in those areas.

As expected based on the road vulnerability, the risk to road damage is not high (see Figure 29). Only roads with a width of less than 4m and roads with a width of 5 to 12m which are prone to higher PGA levels (400-500 cm/s^2) are at medium risk to damage. All the other roads are determined to have low risk to damage.

The determined damage grades for the buildings show that most buildings are expected to receive damage grade 3 or 4 according to the EMS-98 damage scale. Mainly contributing to this is the large number of masonry buildings and the reinforced concrete buildings that are constructed before 1980. Figure 31 shows that Molla Gürani is most prone to building damage as almost half (43.8%) of the buildings with damage grade 4 are located there.

Most parts within the area show low systemic risk with just 13.8% of the roads having medium systemic risk. The roads with medium systemic risk are those with medium systemic vulnerability and very high road closure risk or high road closure risk in combination with a relatively close distance to the liquefaction zones. These roads are mainly present in the south and southwest of Sehremini and around the road in Molla Gürani that connects the two main roads of the case study area (see Figure 40).

The results on the building damage grades can be evaluated by comparing them to the results of JICA & IMM (2002). Like in this study, their cause of building damage is limited to earthquakes. Thus, not including liquefaction, fires and landslides. Differently, they use three classes to present the building damage grades: 'heavily', 'moderately' and 'partly'. 'Heavily' refers to buildings with damage grade 4 or 5 according to the EMS-98 damage scale. 'Moderately' refers to buildings with damage grade 3. 'Partly' refers to buildings with damage grade 2. Another difference with the current study is their resolution of the results. They present their results on administrative boundaries that subdivide the three neighbourhoods of the case study area into multiple smaller areas. Since this study presents the damage grade on building-scale, identifying areas that are at greater risk to building damage becomes more precise. Visual interpretation of their predictions made for the same earthquake event as used in this study shows that a significant part of Topkapi has the highest ratio of 'heavily' damaged buildings with 20-30% being classified as such. The other areas show to have 10-20% 'heavily' damaged buildings. This is different from the results as presented in this study. Their number of buildings with damage grade 4 or 5 are significantly lower and Topkapi does not show to be most prone to earthquake damage. This is likely the result of applying different methods to determine the building damage grades.

According to Milutinovic & Trendafiloski (2003), an earthquake that causes an intensity of X as is the case for this study, should results in many (approximately 15% to 55%) buildings of vulnerability class B to have damage grade 5, many (approximately 15% to 55%) buildings of vulnerability class C to have damage grade 4 and a few (less than approximately 15%) of grade 5 (See Appendix C). In Molla Gürani, which mainly includes buildings of vulnerability class B, 'most' buildings have damage grade 4. In the other two neighbourhoods, that mostly have buildings with vulnerability class B and C, 'many' buildings have damage grade 4. Based on this, it can be said that even though there is a difference with JICA & IMM (2002), the results of this study are still realistic. It has to be noted, that the applied intensity in this study is based on a mathematical conversion from the PGA levels as presented by JICA & IMM (2002). Using another conversion equation could cause different intensities to exist within the case study area, influencing the results on the building damage grades. However, the applied conversion equation is considered most appropriate, because it is based on a Turkish (local) dataset.

Next to the uncertainties of the vulnerability indicators as discussed in RQ 2.1 and RQ 2.2, additional uncertainties within the determined risk indices include the applied hazard models. These models are all taken from JICA & IMM (2002), which provided the models with a relatively coarse resolution. Besides this, the study is relatively outdated, because it is from 2002. It is possible that current studies would provide a different 'worst-case scenario' earthquake model, because over time additional insights on the movement and related accumulation of energy on the fault line can cause the determined probability and expected magnitude of earthquakes to change.

Lastly, six uncertainties were identified when estimating the travel time for the emergency services and distance to the liquefaction zones as described in Section 4.1.4. This could have affected the closest distances and shortest travel times as determined by the network analyses, affecting the systemic risk.

- The merged road networks are slightly differed in some parts of the roads. By combining them, both lines which should represent the same road have remained.
- Most of the applied road velocities are based on an assumption of JICA & IMM (2002).
- The conversion of the road lines to a network might have caused some inaccurate junctions.
- The middle point of the roads was selected to be the target for the network analysis while some roads can be quite long.
- Visual interpretation of the point data for the liquefaction zones could have caused inaccuracies.
- The risk for the liquefaction zones to occur is not distinguished; high risk liquefaction zones have been assumed to have the same effect on the traffic as low risk liquefaction zones.

RQ 2.4 Where can the identified potential disruptions occur?

In contrast to what initially was expected from Section 2.1.4, the results as described in Section 4.2 show that the roads will not be greatly damaged in case of an earthquake event. However, due to the large number of densely built, heavily damaged buildings there exists a high to very high risk for road blockages caused by the debris from buildings in the narrow streets of the case study area, especially in Molla Gürani and Sehremini (see Figure 35). The major roads of the case study area are not in danger of being closed by debris.

Due to the high socioeconomic vulnerability and related low risk awareness and risk preparedness, unfitting behaviour of people can be expected. People will move out of the densely urbanized case study area to the coasts of Fatih by car during an earthquake event, as there are no open spaces available. Consequently, there will be a lot of traffic on the main roads and within the neighbourhoods which contributes to traffic congestions, especially in and around Molla Gürani. Besides this, the inappropriate behaviour is likely to cause the collapse of communication networks, because not only people who live in the area, but also in the rest of Istanbul, will start to use the available communication networks to reach out to for example their families. Communication issues are not necessarily a potential disruption that can be allocated to a certain area. It will affect the disaster management organisations and emergency services everywhere.

An uncertainty was found when determining the road closure risk in the case study area. The amount of building debris resulting from building damages used for the road closure analysis is based on an assumption that only depends on the grouped number of stories and damage grades of the buildings. According to a contact person at the Kandilli Observatory, in reality, the amount of debris is also depending on the building typology, and a more precise distinguishment between the damage grades and height of the buildings. Consequently, the used debris could be different than in reality and as a consequence affect the road closure risk and systemic risk as presented in Sections 4.2.3 and 4.2.4.

In addition, although the impact of liquefaction, traffic intensity and speed limits that are present outside of the case study area have been included to determine the systemic risk, the area is in some aspects still treated as an 'island'. This means that the impact from the areas surrounding the case study area on the vulnerability, risk and potential disruptions are not included to a large extent. Take for example the road closure risk. The roads at the outer bounds of the case study might be impacted by debris from buildings that are located outside of the area, increasing the road closure risk at those location.

RQ 2.5 How could these disruptions potentially impact the traffic control?

The high and very high risk to road closures in several parts within the neighbourhoods will likely cause them to be isolated, reducing access for the emergency services that prevent them from providing support. The traffic jams could cause the emergency services as well as the general public to not be able to manoeuvre quickly to and away from the areas that are most impacted. Lastly, communication issues prevent the disaster management organisations like the AKOM to coordinate the actions of themselves and those of the emergency services due to reduced information-sharing. This might slow down the emergency response and prevent them from operating properly. Eventually, all three disruptions could contribute to the loss of lives and injuries.

RQ 3.1 How to develop a 3D model for this purpose?

The studies that have been found in literature which visualise the vulnerability and risk in an area all apply procedural 3D modelling. The reasons for that are the ease of modelling operability, the possible combination with the commonly available GIS data and the potentially clear visual representation of the city and desired attributes. This approach uses Computer Generated Architecture (CGA) rules to create the 3D objects and define the facades, roofs, windows, etc. in different Levels of Detail. In this study, 3D buildings models of LoD1 were created by extruding the 2D building footprints based on the related building height information using a CGA rule. The same CGA rule applies a colour scheme to the buildings from green to red representing low to high vulnerability or damage degree. Besides this, ESRI's 'Street_Modern_Standard.cga' rule is applied to the shapefile of the road network to create textured roads. By slightly adjusting the code, the roads are given a colour depending on their different vulnerability and risk attributes.

Redweik et al. (2017) suggests to use a Level of Detail of more than LoD1 for the 3D modelling of areas smaller than city-scale. Since this study used LoD1 due to time limitations, the effect from using 3D models in disaster management as found in this study might be less significant. A higher LoD could for example increase the recognition value of the area and its buildings. Consequently, the results might become more convincing and useful for the communication of disaster risk.

Besides this, applying a colour scheme for the visualisation of for example the damage grades of the buildings instead of more realistic textures could have reduced the communication of the actual expected damage to buildings. As stated by Redweik et al. (2017), colour only indicates the relative severity of the damage, but does not show what might happen to the buildings. However, since the purpose of this study is to show which areas are more at risk and where potential disruptions are more likely to occur, visualising the vulnerability and risk using colours is considered more appropriate.

RQ 3.2 How does using the third dimension contribute to the understanding of potential disruptions?

This study found that the third dimension contributes to the communication of the cause of the potential disruptions. It especially investigated the application of the third dimension in understanding the cause of road blockages by debris from buildings. By analysis of Figure 36, Figure 37 and Figure 38, it can be said that the additional dimension makes it more easier to communicate that the roads which are at high or very high risk to road closure are usually accompanied by several 'very heavily damaged' buildings alongside the roads. On top of that, it more clearly shows that these buildings are densely built and are relatively heigh in comparison to the width of the roads. Since the ratio of building height and road width are main factors for road closure, being able to present this with the third dimension is highly beneficial for communication of the risk. Besides this, showing the 3D models contributes to the sense of how dense the case study area is. As a result, it becomes easier to imagine that the people who stay within the neighbourhoods will want to move to the open areas because of this high density.

RQ 4.1 What potential disruptions in the case study area have already been identified in 2D analyses?

The only potential disruption that has been found in literature which could impact the traffic control in the case study area is the risk for road blockages as a result from building debris during an earthquake event. This has been studied by both JICA & IMM (2002) and Cakti et al. (2019). Their road closure analyses are used to evaluate the results as presented in this study.

RQ 4.2 Where do these potential disruptions occur within the case study area?

JICA & IMM (2002) analysed the impact of the same earthquake event as used in this study. They visualise the results of their road closure analysis on a grid with cells of $500m^2$. The results show that all the roads with a width of 2-6m in the entire case study have an 50% or higher probability of being blocked. Roads with a width of 7-15m mostly have a probability of 20-30% or 30-50% of being blocked, especially in Sehremini and Molla Gürani. Other areas have a probability of 10-20%. Lastly, roads with a width of over 16m mostly show to have a probability of 0.1-0.3%, with some parts of the area showing a probability of 0.3-1%. Based on the road blockage probability of roads with a width of 2-6m and 7-15m, the study determined that the entire case study area is at very high risk of being isolated.

The road closure analysis of Cakti et al. (2019) can only be used to evaluate the pattern of road closures as determined in this study, because they applied a different earthquake scenario for their analysis. Cakti et al. (2019) visualise the results on a grid of 0.005x0.005 degrees. Although, visual interpretation of the results was challenging due to the resolution of the provided figures, an attempt was made to get an idea on the risk for road closures. It shows that within the study area, there are 1-5 or 6-10 points where total road closure of one-lane roads per cell can occur. A significant number of two-lane roads within the area is expected to be blocked, especially in Molla Gürani and Sehremini. In these neighbourhoods there are 11-20 or 21-27 points where total road closure can occur, and there are mainly 11-20 or 21-35 points where partial road closure can occur. In Topkapi this risk is less since it mostly shows 1-5 points where total road closure of two-lane roads can occur. Lastly, partial road closure of three-lane roads is also present in the case study with 1-5 points per cell of partial road closure being present in the area. Note that the width of a lane as used by Cakti et al. (2019) is 3 metres wide.

Thus, in both the studies, the neighbourhoods Molla Gürani and Sehremini show to be more prone to road closure than Topkapi. JICA & IMM (2002) show very high road closure for narrow roads (0-7m) and a medium to high road closure risk in somewhat wider roads (7-15m). Similarly, Cakti et al. (2019) show that roads with one- or two lanes (up to 6m wide) have a large number of points where partial or total road closure is possible. Larger roads (that are over 16m wide) are not a high risk to being blocked.

RQ 4.3 How do the identified potential disruptions differ from the results of the 3D model?

After comparing the road closure risk within the case study area according to JICA & IMM (2002) and Cakti et al. (2019) with this study, it became clear that they are very similar. All three studies show that Molla Gürani and Sehremini are most prone to road blockages. Besides this, the large number of narrow roads (0-8m) with high or very high closure risk (over 50%) as determined by this study is in line with the high probability (over 50%) of blockages on narrow roads (0-7m) as determined by JICA & IMM (2002) and the large number of points for partial and total road closure of one- and two-lane roads (0-6m) as determined by Cakti et al. (2019). When the roads become wider, the road closure risk reduces, with roads over 16m wide showing almost no closure risk in all three studies.

Slight differences were found in the location of road blockages. The roads of 7-15m wide in JICA & IMM (2002) and the two-lane roads with total road closure in Cakti et al. (2019) show to be less prone to road blockages in the eastern part of Molla Gürani and the northern part of Sehremini than in this study. However, this difference could be explained by the resolution of the results. While both JICA & IMM (2002) and Cakti et al. (2019) determine the road closure risk based on a grid with a resolution of

500m^2 and 0.005x0.005 degrees, respectively, this study provide the results on road closure risk for each separate road segment. Consequently, it provides a more precise analysis on where blockages could occur. Eventually, this allows for more precisely, spatially located interventions.

RQ 5.1 What structural interventions can be introduced in the historical peninsula to reduce the disaster risk?

As described in Section 4.3.1, it is suggested to apply seismic retrofitting to several buildings and to introduce local gathering facilities for spontaneous rescue teams and fire hydrants within the case study area. Seismic retrofitting increases the structural strength of buildings which reduces the risk for collapse and heavy damage and ,with that, the risk for injuries, loss of business and building debris. As a consequence, both the road closure risk and systemic risk are reduced. The buildings that are suggested for this intervention are expected to be ‘very heavily damaged’, contribute to very high road closure risk, an increased systemic risk, and are located in building blocks without any listed buildings (see Figure 41).

The local gathering facilities aid spontaneous rescue teams and the emergency services by providing with a place and necessary resources for the coordination of rescue and clean-up activities. The suggested locations are buildings and open spaces which will remain accessible during the earthquake event. Resources can include among others satellite phones, speakers, portable generators, fuel, medical aid kits, food and water. Additionally, locations for fire hydrants are suggested to aid the fire brigade in their activities. These are located in areas that will become isolated, near heavily damaged buildings which are assumed to be a source of ignition (see Figure 42).

It is uncertain whether the locations of the proposed structural interventions are suitable. One of the reasons is that it is unknown where the listed heritage buildings are located. This was based on an assumption due to the lack of data. Besides this, it might not be possible to use the suggested buildings as local gathering facilities and for the storage of resources when their current use and potential storage capabilities are considered. However, this study does identify multiple locations which are shown to be critical and could still provide several realistic options.

RQ 5.2 What non-structural interventions can be introduced in the historical peninsula to reduce the disaster risk?

As described in Section 4.3.2, this study suggest to raise awareness, provide incentives for those who need it the most and promote micro-mobility. Raising awareness can be done by spreading information on disaster related topics via booklets, the media, recurring, interactive, participatory education sessions and earthquake safety exhibitions. Such topics can include the mitigation, preparedness, response and recovery phases of disaster, disaster legislation and essential skills for response and recovery.

By providing the general public with incentives, they can make themselves more resilient by taking risk mitigation measures. People who require such incentives the most are thought to be the ones that have a low-income and live in damage-prone buildings. That is why it is suggested to focus on the neighbourhoods with the lowest-income levels, Topkapi (Table 14), and most buildings with damage grade 4, Molla Gürani (Figure 31). The compulsory earthquake insurance that was implemented in Turkey in 2000 provide homeowners with an insurance for building damages caused by earthquakes. Since this focusses on post-earthquake aid, introducing pre-earthquake aid could increase resilience. Besides this, the premium that needs to be paid to get the insurance depends on the Turkey Earthquake Zone in which the building is located, the ground conditions, building characteristics and building size (Yazici, 2006). Consequently, people who live in the more vulnerable buildings in earthquake-prone zones, pay a higher premium. By providing such people who also have a low-income with incentives, they will be able to improve their building characteristics, making them less vulnerable and additionally more likely to pay lower insurance premiums.

By introducing micro-mobility it is likely that the access to public transportation improves, the taxi and private car rides reduces, and the already scare space in the case study is used more efficiently. This should help to reduce emissions, reduce traffic, reclaim space for citizens and improve the quality of life. Introducing it does require new policies, a safe micro-mobility infrastructure, innovation and responsible business practices which will take quite some investments and time. As such, the effect from this will likely become apparent on the long-term rather than the short-term. However, introducing this should be beneficial in the end.

Additional non-structural measures are necessary for the implementation of local gathering facilities as described in Section 4.3.1. It is important to appoint and train personnel for the coordination of the rescue and clean-up activities of the volunteers. Besides this, the facilities need to be managed to make sure resources are available at all times. Lastly, local people who want to volunteer need to know where such facilities are located, so it is important to raise awareness about this.

Main research question: What is the additional value of including the third dimension in disaster risk reduction?

Based on the comparison with JICA & IMM (2002) and Cakti et al. (2019), it can be said that the third dimension improves the understanding on potential disruptions and the recognition of the morphology in an urban area. As discussed in RQ 3.2, it was found that it becomes clearer how the height and density of the buildings around the roads contribute to the (size and likeliness of the) road blockages. Besides this, the communication of the potential for traffic jams that could occur during an earthquake event is more convincing with 3D models than 2D maps, because it is more apparent how dense an area actually is. This was expected by the spokespersons from the ITU and the IPA who thought that the 3D models would improve the understanding of what problems could occur during an earthquake event, especially problems related to density like road closure. Besides this, they mentioned that 3D models are much more convincing than two dimensional representations.

Moreover, by using 3D models the morphology of an area becomes more apparent. Visualising the building damage grades in the third dimension, makes it easier to recognize buildings that are at higher risk, and as a results could cause debris. This should become even more apparent when using a higher LoD. This benefit was also mentioned by the IPA, AKOM and fire brigade who believed that 3D models are likely to be beneficial in understanding the morphology of the area which could help to identify buildings more easily.

Having a better understanding on the causes of the potential disruptions, especially the road blockages, and by being able to communicate the morphology of an area better, decision-making by the disaster management organisation such as the AFAD, IMM and Fatih Municipality on local risk mitigating measures could be improved. Besides this, it might aid disaster coordinating organisation such as the AKOM in creating more dynamic actions plans that include the effect of interrelated components causing the disruptions.

5.2 Summary

The increased number of city networks such as 100 Resilient Cities and Global Resilient City Networks, proves the importance of making cities disaster resilient. The major difficulty on this trajectory is the interrelated components, such as built-up environment, people, organisations, technology and economy, in urban systems that influence each other and increase uncertainty in the risk assessment and management. Istanbul is such an urban system in need of becoming more resilient. The megacity that is at increased risk to earthquakes due to the east to west progression of epicentres along the North Anatolian Fault (Atun & Menoni, 2014). Next to this, Istanbul has shown to be at risk to the cascading effects such as fire, liquefaction and tsunamis (Alpar et al., 2003; JICA & IMM, 2002; Pampanin, 2021). Contributing to the risk that exist in Istanbul are the many weak structures, densely urbanized and populated areas, a great amount of traffic causing traffic jams and the many people from the low socioeconomic groups (Atun & Menoni, 2014). These aforementioned hazards and causes of vulnerability are also present in the case study area. This exists of three neighbourhoods, Sehremini, Topkapi and Molla Gürani, which are located in the historical peninsula of Istanbul named Fatih, known to be the heart for tourism and transportation.

Existing seismic vulnerability and risk assessments provide results in two dimensions. According to Hollnagel et al. (2006), two-dimensional representations (e.g. maps and plans) do not take the effects from a changing environment with interrelated components into account sufficiently. As a result, potential disruptions in the city caused by earthquakes can be overlooked and with that the existing plans can become unapplicable to the real situation. Thus, the research problem is that static solutions are provided for a dynamic and complex environment. This study focusses on potential disruptions within traffic control which refers to operational procedures that guide the evacuation of vehicles and access of emergency services to and from disastrous areas. It is important that the traffic control remains functional during an earthquake. Therefore, it is essential to understand the causes of the potential disruptions that could occur. This way, measures can be taken that reduce the impact of earthquakes on traffic control in such a dynamic environment.

This study analyses the potential disruptions that impact traffic control with the help of multi-hazard risk assessment (i.e. earthquakes, fires, and liquefaction). Moreover, it introduces the use of 3D models for the visualisation of disaster risk. Research has proved that 3D models reduce the cognitive effort required to analyse the situation and improve the communication of results in comparison to two-dimensional representations (Redweik et al., 2017). Therefore, by using 3D models, environmental interactions should become more apparent which makes it possible to better understand the underlying causes of disruptions that could impact traffic control and based on that suggest more dynamic solutions.

In order to identify which potential disruptions are likely to happen in the case study area, three historical earthquake events (the Kobe earthquake in 1995, the Tohoku earthquake in 2011 and the Christchurch earthquake in 2011) were analysed. During these events, the traffic control was impacted due to disruptions caused by the earthquakes. Disruptions that are considered applicable to the case study area are road damage, road blockages by debris, traffic congestions and communication issues. These have shown to disrupt coordination among disaster management bodies and to delay or even prevent emergency services from reaching impacted areas.

For the current study, the additive normalization indicator-based approach is used to assess the socioeconomic, road and systemic vulnerability and risk in the case study area. Besides, the EMS-98 Macroseismic method is applied to determine the building vulnerability and damage grades. In addition, based on these results, the potential for disruptions as found in literature are analysed. This includes a road closure analysis. The buildings and roads with their corresponding vulnerability and risk indices are visualised in 3D. This is done using procedural 3D modelling. The buildings are modelled with Level of Detail 1 and a colour scheme is applied to clearly distinguish between the corresponding vulnerability and risk levels of the buildings and roads.

The results show that the roads in the case study are not prone to damage. However, almost half of the roads are expected to be blocked by debris from buildings. These mainly include roads that are up to 8m wide and are located in Molla Gürani and Sehremini. This can be attributed to the large number of 'very heavily damaged' buildings in the area. Especially, Molla Gürani shows to be in danger of receiving significant building damage during the applied earthquake event. The socioeconomic vulnerability in the area is also shown to be high, especially in Molla Gürani. As a consequence, it is expected that inappropriate human behaviour such as chaotic evacuation and excessively using the communication networks will cause traffic congestions and the communication between disaster management organisations and emergency services to become problematic. All this contributes to the increased systemic vulnerability and risk in the south and southwest of the neighbourhood Sehremini and around the road in Molla Gürani that connects the two main roads of the case study area.

The results of this study show to be in line with the study on social vulnerability by Ugur et al. (2018) and the study on road closure risk by both JICA & IMM (2002) and Cakti et al. (2019). The estimated building damages do show differences with JICA & IMM (2002). However, based on the definition of the applied earthquake intensity in this analysis according to the EMS-98 intensity scale, the results are still realistic. One of the advantages of this study is that it provides a greater resolution on the road and building vulnerability and risk, and the potential for road blockages. As a results, disaster mitigating measures can be suggested more locally. Contributing to this, is the applied third dimension. The 3D visualisations made it clearer that the roads where the road closure risk is high are surrounded by damage-prone buildings, that are constructed very densely and are heigh relative to the narrow roads. Besides this, the 3D models are more convincing in communicating that other potential disruptions, such as the occurrence of traffic jams, are realistic, because it is more apparent how dense the area actually is. Lastly, by using 3D models, the morphology of an area becomes more apparent as buildings are easier to identify. Concluding, the additional value of including 3D modelling in disaster risk reduction is that it makes it easier to recognize the morphology of an area and that it contributes to the understanding and communication of the underlying causes of potential disruptions. This could help decision-makers in suggesting more local measures that mitigate the underlying causes of the potential disruptions and help disaster coordinating organisation in preparing more dynamic action plans.

5.3 Limitations and future research

As discussed in Section 5.1, some indicators were excluded and proxies were used for the vulnerability and risk assessments due to the lack of data. That is why it is suggested to collect and apply additional data that has been identified to be missing in this study and is considered important to understand the vulnerability, risk and potential disruptions. As a consequence, the results might become more realistic and, with that, more suitable for suggesting interventions.

Due to time limitations, this study applied LoD1 to the created 3D models, instead of higher LoDs as suggested by Redweik et al. (2017). Therefore, for future research the use of a higher LoD is suggested. Besides this, it is advised to discuss the interpretation of the results of the 3D models with the stakeholders and other academics. As they are the ones for who this novel approach is introduced, knowing how they look at the results and getting feedback on the interpretation could be very interesting and useful for scientific purposes. Thus, overall it is suggested to further explore the application of the third dimension in disaster risk management, because this study has found that there are benefits in using 3D models in the communication of risk and the causes of potential disruptions.

Lastly, it is advised to involve local stakeholders (e.g. building owners and the Fatih municipality) when suggesting the locations for the local gathering facilities. They have more knowledge on the current use and storage capacities of the locations.

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Appendices

Appendix A : Structure prepared for the semi-structured interviews

Start interview

- Ask for consent for recording the interview.
- Introduction to my topic and thesis.
- Explain why I want to interview this person.

Questions

Relation to the thesis topic
- How is your job related to the risk of earthquakes or, in general, disaster risk?
- What operational procedures do you have during or after an earthquake event?

Problems that are faced
- What daily challenges do you face and how do you tackle them?
- What problems did/can you face in your operational procedures during earthquakes?
- How do you consider the impact of earthquakes on traffic control in what you do?
- What characteristics of the case study area do you think cause it to be very vulnerable and at high risk?

Mitigation measures
- What are current plans to reduce the disaster risk?
- What do you think are important additional actions to reduce disaster risk, focussing on traffic control?

Significance of 3D models
- What data do you use in your activities?
- Do you think using a third dimension for communication purposes could be beneficial?

Ending interview

- Are you interested in receiving my thesis after I am finished to see the results?
- Thank the interviewee for their time.

Appendix B : Tables from literature used for the EMS-98 Macroseismic method

Tables 17, 18, 19 and 20 show the vulnerability classes and values given to buildings depending on their typology. Tables 21, 22, 23, 24 and 25 show an overview on the values of the behaviour modifier factors used for the EMS-98 Macroseismic method.

Table 17: Relation of the vulnerability classes to the different building typologies. Source: Giovinazzi & Lagomarsino (2004, p. 7)

Typologies		Building type	Vulnerability Classes					
			A	B	C	D	E	F
	M1	Rubble stone						
	M2	Adobe (earth bricks)						
	M3	Simple stone						
	M4	Massive stone						
	M5	Unreinforced M (old bricks)						
	M6	Unreinforced M with r.c. floors						
	M7	Reinforced or confined masonry						
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)						
	RC2	Frame in r.c. (moderate E.R.D.)						
	RC3	Frame in r.c. (high E.R.D.)						
	RC4	Shear walls (without E.R.D)						
	RC5	Shear walls (moderate E.R.D.)						
	RC6	Shear walls (high E.R.D.)						
Stell	S	Steel structures						
Tiber	W	Timber structures						

Situations: Most probable class; Possible class; Unlikely class (exceptional cases)

Table 18: Vulnerability indices for the different building typologies. Source: Giovinazzi & Lagomarsino (2004, p. 8)

Typologies		Building type	ulnerabilità Classes				
			$V_{I\,min}$	V_I^-	V_I^*	V_I^+	$V_{I\,max}$
Masonry	M1	Rubble stone	0.62	0.81	0.873	0.98	1.02
	M2	Adobe (earth bricks)	0.62	0.687	0.84	0.98	1.02
	M3	Simple stone	0.46	0.65	0.74	0.83	1.02
	M4	Massive stone	0.3	0.49	0.616	0.793	0.86
	M5	Unreinforced M (old bricks)	0.46	0.65	0.74	0.83	1.02
	M6	Unreinforced M with r.c. floors	0.3	0.49	0.616	0.79	0.86
	M7	Reinforced or confined masonry	0.14	0.33	0.451	0.633	0.7
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)	0.3	0.49	0.644	0.8	1.02
	RC2	Frame in r.c. (moderate E.R.D.)	0.14	0.33	0.484	0.64	0.86
	RC3	Frame in r.c. (high E.R.D.)	-0.02	0.17	0.324	0.48	0.7
	RC4	Shear walls (without E.R.D)	0.3	0.367	0.544	0.67	0.86
	RC5	Shear walls (moderate E.R.D.)	0.14	0.21	0.384	0.51	0.7
	RC6	Shear walls (high E.R.D.)	-0.02	0.047	0.224	0.35	0.54
Stell	S	Steel structures	-0.02	0.17	0.324	0.48	0.7
Tiber	W	Timber structures	0.14	0.207	0.447	0.64	0.86

Table 19: Vulnerability indices for the different building typologies. Source: Milutinovic & Trendafiloski (2003, p. 29)

Typology	Description	V_I representative values				
		$V_{I,BTM}^{min}$	$V_{I,BTM}^{-}$	$V_{I,BTM}^{*}$	$V_{I,BTM}^{+}$	$V_{I,BTM}^{max}$
M1.1	*Rubble stone, fieldstone*	0.62	0.81	0.873	0.98	1.02
M1.2	*Simple stone*	0.46	0.65	0.74	0.83	1.02
M1.3	*Massive stone*	0.3	0.49	0.616	0.793	0.86
M2	*Adobe*	0.62	0.687	0.84	0.98	1.02
M3.1	*Wooden slabs*	0.46	0.65	0.74	0.83	1.02
M3.2	*Masonry vaults*	0.46	0.65	0.776	0.953	1.02
M3.3	*Composite steel and masonry slabs*	0.46	0.527	0.704	0.83	1.02
M3.4	*Reinforced concrete slabs*	0.3	0.49	0.616	0.793	0.86
M4	*Reinforced or confined masonry walls*	0.14	0.33	0.451	0.633	0.7
M5	*Overall strengthened*	0.3	0.49	0.694	0.953	1.02
RC1	*Concrete Moment Frames*	-0.02	0.047	0.442	0.8	1.02
RC2	*Concrete shear walls*	-0.02	0.047	0.386	0.67	0.86
RC3.1	*Regularly infilled walls*	-0.02	0.007	0.402	0.76	0.98
RC3.2	*Irregular frames*	0.06	0.127	0.522	0.88	1.02
RC4	*RC Dual systems (RC frame and wall)*	-0.02	0.047	0.386	0.67	0.86
RC5	*Precast Concrete Tilt-Up Walls*	0.14	0.207	0.384	0.51	0.7
RC6	*Precast C. Frames, C. shear walls*	0.3	0.367	0.544	0.67	0.86
S1	*Steel Moment Frames*	-0.02	0.467	0.363	0.64	0.86
S2	*Steel braced Frames*	-0.02	0.467	0.287	0.48	0.7
S3	*Steel frame+unreinf. mas. infill walls*	0.14	0.33	0.484	0.64	0.86
S4	*Steel frame+cast-in-place shear walls*	-0.02	0.047	0.224	0.35	0.54
S5	*Steel and RC composite system*	-0.02	0.257	0.402	0.72	1.02
W	*Wood structures*	0.14	0.207	0.447	0.64	0.86

Table 20: Vulnerability indices for the different building typologies. Source: Redweik et al. (2017, p. 313)

	Sousa (2006)		European project *Risk-UE*	
Construction typology	Construction epoch	Class	Designation	Seismic vulnerability index (V_I^*)
Adobe, Stone		A	M2	0.840
Other (Metalic)		E	S1	0.363
Masonry without RC floor	Before 1919	B	M1.1	0.873
	1919–1960	B	M1.2	0.740
	1961–1980	C	M3.4	0.616
	1981–2011	D	M4	0.451
Masonry with RC floor	Before 1919–1980	C	M3.4	0.616
	1980–2011	D	M4	0.451
Reinforced concrete	1919–1960	C	RC1	0.442
	<8Fl			
	1961–1980	C	RC1	0.442
	>8Fl			
	1961–1980	D	RC2	0.386
	1980–2011	D	RC2	0.386

Table 21: Scores for behaviour modifier factors for masonry and reinforced concrete buildings. Source: Giovinazzi & Lagomarsino (2004, p. 9)

Behaviour modifier	Masonry		Reinforced Concrete ERD Level	Pre/Low	Medium	Hight
		V_{mk}		V_{mk}	V_{mk}	V_{mk}
State of preservation	Good	-0.04	Good	-	-	-
	Bad	+0.04	Bad	+0.04	+0.02	0
Number of floors	Low (1or 2)	-0.04	Low (1-3)	-0.02	-0.02	-0.02
	Medium (3,4 or 5)	0	Medium (4-7)	0	0	0
	High (6 or more)	+0.04	High (8 or more)	+0.08	+0.06	+0.04
Structural system	Wall thickness Wall distance Wall connections	-0.04÷+0.04				
Plan Irregularity	Geometry	+0.04	Geometry	+0.04	+0.02	0
	Mass distribution		Mass distribution	+0.02	+0.01	0
Vertical Irregularity	Geometry Mass distribution	+0.04	Geometry Mass distribution	+0.04	+0.02	0
Superimposed flors		+0.04				
Roof	Weight, thrust and connections	+0.04				
Retroffiting Intervention		-0.08÷+0.08				
Aseismic Devices	Barbican, Foil arches, Buttresses	-0.04				
Aggregate Building: position	Middle	-0.04	Insufficient aseismic joints	+0.04	0	0
	Corner	+0.04				
	Header	+0.06				
Aggregate Building: elevation	Staggered floors	+0.04				
	Buildings with different height	-0.04÷+0.04				
Foundation	Different level foundations	+0.04	Beams	-0.04	0	0
			Connected beams	0	0	0
			Isoleted Footing	+0.04	0	0
			Short-column	+0.02	+0.01	0
			Bow windows	+0.04	+0.02	0

Table 22: Scores for behaviour modifier factors for masonry buildings. Source: Milutinovic & Trendafiloski (2003, p. 31)

Vulnerability Factors	***Parameters***	
State of preservation	Good maintenance Bad maintenance	-0,04 +0.04
Number of floors	Low (1 or 2) Medium (3, 4 or 5) High (6 or more)	-0.02 +0.02 +0.06
Structural system	Wall thickness Distance between walls Connection between walls (tie-rods, angle bracket) Connection horizontal structures-walls	-0,04 ÷ +0,04
Soft-story	Demolition/ Transparency	+0.04
Plan Irregularity	…	+0.04
Vertical Irregularity	…	+0.02
Superimposed floors		+0.04
Roof	Roof weight + Roof Thrust Roof Connections	+0.04
Retrofitting interventions		-0,08 ÷ +0,08
Aseismic Devices	Barbican, Foil arches, Buttresses	
Aggregate building: position	Middle Corner Header	-0.04 +0.04 +0.06
Aggregate building: elevation	Staggered floors Buildings of different height	+0.02 -0,04 ÷ +0,04
Foundation	Different level foundation	+0.04
Soil Morphology	Slope Cliff	+0.02 +0.04

Table 23: Scores for behaviour modifier factors for reinforced concrete buildings. Source: Milutinovic & Trendafiloski (2003, p. 32)

Vulnerability Factors		*ERD level*		
		Pre or Low Code	*Medium Code*	*High Code*
Code Level		+0,16	0	-0,16
Bad Maintenance		+0.04	+0.02	0
Number of floors	Low (1 or 2)	-0,04	-0,04	-0,04
	Medium (3, 4 or 5)	0	0	0
	High (6 or more)	+0,08	+0,06	+0,04
Plan Irregularity	Shape	+0.04	+0.02	0
	Torsion	+0.02	+0.01	0
Vertical Irregularity		+0.04	+0.02	0
Short-column		+0.02	+0.01	0
Bow windows		+0.04	+0.02	0
Aggregate buildings (insufficient aseismic joint)		+0,04	0	0
Foundation	Beams	-0,04	0	0
	Connected Beans	0	0	0
	Isolated Footing	+0,04	0	0
Soil Morphology	Slope	+0.02	+0.02	+0.02
	Cliff	+0.04	+0.04	+0.04

Table 24: Scores for behaviour modifier factors for masonry buildings. Source: Redweik et al. (2017, p. 313)

Behavior modifying factor	Parameters	$(\Delta V_m)_i$
Preservation	Good	−0.04
	Bad	+0.04
Number of floors	Low (1–2)	−0.02
	Medium (3, 4, or 5)	+0.02
	High (6 or more)	+0.06
Building position in block	Middle[a]	−0.04
	Corner	+0.04
	Header[b]	+0.06

[a]The building has two adjacent buildings

[b]The building has one adjacent building (three free sides)

Table 25: Scores for behaviour modifier factors for reinforced concrete buildings. Source: Redweik et al. (2017, p. 313)

Behavior modifying factor	$(\Delta V_m)_i$	
	Pre-code or low level	Middle level
Seismic dimensioning code level	+0.16	0
Bad preservation	+0.04	+0.02
Number of floors		
Low (1 to 2)	−0.04	−0.04
Medium (3, 4 or 5)	0	0
High (6 or more)	+0.08	+0.06

Appendix C : The EMS-98 Macroseismic intensity levels

Table 26: Definitions of the Macroseismic intensity levels according to Grünthal & Schwarz (1998). Source: Author (2020)

Macroseismic Intensity	Description
I. Not felt	a) Not felt, even under the most favourable circumstances. b) No effect. c) No damage.
II. Scarcely felt	a) The tremor is felt only at isolated instances (<1%) of individuals at rest and in a specially receptive position indoors. b) No effect. c) No damage.
III. Weak	a) The earthquake is felt indoors by a few. People at rest feel a swaying or light trembling. b) Hanging objects swing slightly. c) No damage.
IV. Largely observed	a) The earthquake is felt indoors by many and felt outdoors only by very few. A few people are awakened. The level of vibration is not frightening. The vibration is moderate. Observers feel a slight trembling or swaying of the building, room or bed, chair etc. b) China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. Woodwork creaks in a few cases. c) No damage.
V. Strong	a) The earthquake is felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture. b) Hanging objects swing considerably. China and glasses clatter together. Small, top-heavy and/or precariously supported objects may be shifted or fall down. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from well-filled containers. Animals indoors may become uneasy. c) Damage of grade 1 to a few buildings of vulnerability class A and B.
VI. Slightly damaging	a) Felt by most indoors and by many outdoors. A few persons lose their balance. Many people are frightened and run outdoors. b) Small objects of ordinary stability may fall and furniture may be shifted. In few instances dishes and glassware may break. Farm animals (even outdoors) may be frightened. c) Damage of grade 1 is sustained by many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1.
VII. Damaging	a) Most people are frightened and try to run outdoors. Many find it difficult to stand, especially on upper floors. b) Furniture is shifted and top-heavy furniture may be overturned. Objects fall from shelves in large numbers. Water splashes from containers, tanks and pools. c) Many buildings of vulnerability class A suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class B suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class C sustain damage of grade 2. A few buildings of vulnerability class D sustain damage of grade 1.
VIII. Heavily damaging	a) Many people find it difficult to stand, even outdoors. b) Furniture may be overturned. Objects like TV sets, typewriters etc. fall to the ground. Tombstones may occasionally be displaced, twisted or overturned. Waves may be seen on very soft ground.

	c) Many buildings of vulnerability class A suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class B suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class C suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class D sustain damage of grade 2.
IX. Destructive	a) General panic. People may be forcibly thrown to the ground. b) Many monuments and columns fall or are twisted. Waves are seen on soft ground. c) Many buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class C suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class D suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class E sustain damage of grade 2.
X. Very destructive	c) Most buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B sustain damage of grade 5. Many buildings of vulnerability class C suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class D suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class E suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class F sustain damage of grade 2.
XI. Devastating	c) Most buildings of vulnerability class B sustain damage of grade 5. Most buildings of vulnerability class C suffer damage of grade 4; many of grade 5. Many buildings of vulnerability class D suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class E suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class F suffer damage of grade 2; a few of grade 3.
XII. Completely devastating	c) All buildings of vulnerability class A, B and practically all of vulnerability class C are destroyed. Most buildings of vulnerability class D, E and F are destroyed. The earthquake effects have reached the maximum conceivable effects.

Figure 43: Membership function for the quantities 'few', 'many' and 'most'. Source: Milutinovic & Trendafiloski (2003, p. 27)