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Measuring spatial accessibility to critical infrastructure: The Access Road Identification model

Ana Maria Mager Pozo [a,b,*], Peter Priesmeier [a], Alexander Fekete [a]

[a] Cologne University of Applied Sciences (TH Köln), Institute for Rescue Engineering and Civil Protection, Betzdorfer Straße 2, 50679 Cologne, Germany
[b] German Aerospace Center (DLR), Institute for the Protection of Terrestrial Infrastructures, Rathausallee 12, 53757 Sankt Augustin, Germany

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ABSTRACT

Natural hazards such as earthquakes or floods can severely disrupt transportation networks and lead to cascading effects to other critical infrastructure (CI). A functioning road network is crucial to maintain spatial accessibility of CI such as hospitals or fire stations, especially during disaster scenarios. In the present study, we introduce a geographic information system (GIS)-based model that is able to identify and quantify the access roads to CI facilities through shortest path analysis, namely the Access Road Identification (ARI)-model. Including hazard maps into the model allows comparing CI accessibility in a baseline scenario with a hazard scenario. We exemplary apply the elaborated model to two case studies considering the accessibility of hospitals during floods in Hamburg, Germany and fire stations during an earthquake event in the Tehran-Karaj metropolitan region, Iran.

The results show significant differences between the two case studies: Floods have an overall low impact on the accessibility of hospitals in Hamburg, but single hospitals lose up to 40 % of their access roads during the flood. In Tehran-Karaj however the model indicates that about 38 % of the fire stations have access roads exposed to the earthquake hazard, while a fifth of them lose over 50 % of their access roads and four facilities are completely inaccessible.

These findings highlight the need for robust contingency planning by identifying and prioritizing CI facilities that are most at risk. The novelty of the ARI-model consists in its facility-centered approach to measure spatial accessibility of single CI services, thus unveiling valuable insights regarding the potential loss of direct access roads. The transferability of the model allows to adapt it to various use cases, where different hazards or CI facility types are considered. The model can serve relevant stakeholders as a decision-making tool for prioritizing resource allocation, planning evacuation measures and enhancing disaster preparedness based on CI accessibility, thus being applicable both to the preparation and response phase of disaster management. In the future, an extension of the ARI-model is planned by implementing dynamic hazard maps, data on traffic demand and additional weighting of the results.

1. Introduction

Natural hazards such as earthquakes, floods or storm events can negatively affect people and society, amplified by additional critical infrastructures (CI) failure [1]. The road network as part of the transportation infrastructure of a city or region often suffers direct impact from a hazard, which can lead to blocked roads, damaged bridges or traffic jams and consequently to a disruption or complete loss of spatial accessibility [2–4]. As climate-induced hazards are more likely to increase in the future [5], the impact of natural hazards on road networks is an increasingly important issue. The ability to use the road network as a part of the transportation system safely and efficiently is crucial for rural and urban populations. The damage or disruption of a road network can have severe impact on either directly the population [6,7] or indirectly by affecting other CI [8–10]. Such indirect impacts, also called cascading effects, need special attention, as they are difficult to comprehend and often go unnoticed [11,12].

CI such as hospitals need to be physically accessible at any time, especially during a disaster. In a crisis situation the population's demand on healthcare can increase, leading to a patient number surge [13–15].

* Corresponding author.
E-mail address: anamaria.magerpozo@dlr.de (A.M. Mager Pozo).

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Not only the patient flow but also logistics and providing medical material for an adequate healthcare heavily relies on the accessibility and therefore on a functioning road network surrounding the CI facility [16]. Especially in the case of hospitals, rapid decisions might be necessary in disaster incidents, such as a flooding, to determine whether evacuation is required. Spatial accessibility of healthcare facilities is crucial when planning and executing the evacuation of hazard-affected facilities [17,18]. Evacuating critical patients can have a pronounced detrimental effect on their condition and should only be carried out when truly necessary [19]. Making such a decision requires knowledge of which hospitals are still easily accessible, where evacuation might need to occur sooner, and which hospital might no longer have sufficient access roads for evacuation at certain water levels. Accessibility to functional hospitals is highly important for disaster management and effectively handling crises: Reflected in frameworks like the Sendai Framework for Disaster Risk Reduction [1], this topic is of global relevance.

The same applies to other CI that is relevant for emergency rescue operations, like fire and rescue stations. In the event of a severe earthquake, capable emergency response teams rely on a functional road network to cope with the increased demand of firefighting and rescue services. However, many areas might be blocked by debris or damaged road infrastructure. In such a scenario, it is crucial to quickly determine which fire and rescue stations can adequately serve the surrounding areas and which ones may have restricted capacity in providing emergency response capabilities due to an obstructed road network [20,21]. Fire stations and the dispatch of rescue services is therefore highly dependent of an intact road network. The ability of an ambulance to physically reach a patient in a given time can decide upon success or failure of the rescue operation. A disrupted road network has direct impact on the effectiveness of the emergency rescue system [22]. Thus it is important to assess the spatial accessibility of fire stations to the nearby road network and understand how the accessibility may change in a hazard scenario.

Previous studies often analyze the accessibility of CI services from a population-centered perspective, commonly investigating under-served parts of the population or calculating how many people suffer a certain degree of accessibility reduction during a disaster [23–26]. While this is arguably a very important metric for decision makers before and during a disaster, a perspective that directly focusses on CI facilities (e.g. hospitals, fire stations) and their accessibility seems to be missing. To better understand the cascading effects of damaged CI services on the population and the emergency management system, we propose to conduct an accessibility analysis from a facility-centered perspective, while considering an ongoing hazard scenario. In this facility-centered approach, the focus shifts from the number of affected people to the number of affected CI facilities and on the severity of the respective impact by quantifying the loss of direct access roads. This can provide valuable additional information for disaster managers and stakeholders of urban planning or emergency management to decide which CI facilities have to be protected or evacuated in time. A spatial accessibility analysis can be applied in both the preparation and the response to a hazard in order to take appropriate measures and avoid further loss and damage. Possible measures can be deciding on new CI facility locations, relocating resources for emergency rescue or establishing temporarily emergency response centers.

To address the described research gap, we developed an approach that can identify and prioritize CI facilities during and in the pre-disaster phase, which might be cut-off or strongly reduced in their spatial accessibility due to a non-traversable road network. We present a geographic information system (GIS)-based model, which is automatically able to identify access roads of CI facilities across three different distances to the facility. The model compares the number of access roads to CI facilities in a baseline scenario with a hazard scenario. By recalculating the loss of access roads, our goal is to show which CI facilities are most restricted in their spatial accessibility when the specific hazard strikes. To demonstrate the feasibility and the global transferability of our model we apply it to two different case study areas with different hazards and CI facility types. With the present study we intend on contributing to the research on spatial accessibility of CI services from a facility-centered perspective by providing a GIS-model that can be transferred to different case studies and applied to multiple sectors of CI facilities.

2. Literature review

In general, accessibility is a highly complex and multi-dimensional topic. It is a well-known concept in urban planning and has been applied to several use cases, such as measuring the accessibility to healthcare facilities [27,28], the public transport system [29,30] or urban green spaces [31,32]. Due to its numerous applications, accessibility has varying definitions in research, making it difficult to find a universally valid definition. According to transportation research, and in line with the present study, spatial accessibility can be defined as "the potential to reach spatially distributed opportunities" [33], in this case being the investigated CI facilities. Especially in the context of healthcare, accessibility represents a multi-layered and multi-dimensional concept. Researchers have identified five different dimensions of healthcare access; namely availability, accessibility, affordability, acceptability and accommodation [34]. Spatial accessibility thus only covers one aspect of healthcare access, which should be considered upon further reading. Nonetheless, when facing natural hazards obstructing the road network, spatial accessibility to CI facilities is a relevant topic to investigate.

Many studies focus on road networks and the disruptive effects of disasters on the general supply capacity. These studies look at the road network as the CI service in itself and do not consider the cascading effects on other CI facilities. Abenayake et al. [6] focus on the transportation network of Colombo in Sri Lanka under flooding conditions. Their method uses betweenness centrality and closeness centrality measures to analyze flooding impact on the transportation system for short and long trips. Chamorro et al. [35] also investigate the disaster impact on road networks, but expand their routing optimization analysis by including the physical fragility of the road components and taking the social vulnerability of the exposed population into account. Petricola et al. [7] use a raster and network-based approach to analyze the change in accessibility of the local population affected by cyclone Idai in Mozambique in 2019. A modified centrality indicator allows identifying road segments, which are most likely impacted by flooding, so that potential backup roads can be chosen. The network and raster-based approaches resulted in different outcomes in the number of affected people, which can be attributed to incomplete mapping of the road network [7]. El-Maissi et al. [36] provide a framework for integrated seismic vulnerability of road networks and include a calculation of building debris width, that allows to examine if a road segment is potentially affected by a collapsed building. Such information also enables to determine if the whole road segment is impassable due to the collapsed building or if only single lanes are impassable.

Further studies have been undertaken to take a closer look at direct interdependencies between CI relevant for disaster management, like hospitals, ambulances, fire stations and the road network [37,38]. These studies focus on the high relevance that a functioning road system has on the accessibility of CI services for the population. In their spatial optimization approach Wang et al. [39] use points of interest and traffic data in combination with fire hazard maps to analyze the actual coverage of fire stations in Beijing. Additional 15 fire stations could be identified that would be necessary to cope with the rush hour induced traffic jams [39]. Rohr et al. [22] developed an iterative model that analyzes the criticality of road segments based on the amount of delay caused by a road blockage relevant for fire and rescue vehicles. To improve accuracy, they use emergency call data to include ambulance driving patterns. Freiria et al. [40] propose a link-based model to investigate the access of people to hospitals in the Central Region of Portugal. They include mobility information about the population as well as hospital bed numbers to increase the accuracy of their approach, which combines a gravity model with the widely used two-step floating catchment area method.

Other research investigates the explicit impact of hazards in connection to the interdependency of the road network to CI, which allows to understand the underlying cascading effects. They usually begin with modeling the hazard exposure of the road network and the respective failures of the transportation system. This is followed by an impact analysis of the disrupted transportation system that influences the functionality of the CI facility. Mossoux et al. [41] for example analyze lava flow on Ngazidja Island in the Comoros archipelago in Africa and elaborate a model that calculates the degree of affectedness of the local population based on their accessibility to hospitals. The novelty of their model lies in the inclusion of the hazard's probability in the road failure calculation, which again influences the hospital access and therefore the impact on the population. The study by Dong et al. [42] models hazard-based access disruption due to floods by measuring network robustness and also considers the social vulnerability of the exposed population. The focus of the study are communities in Harris County U.S., which are likely to suffer from lower hospital access during a disaster, and are highly vulnerable at the same time. Tariverdi et al. [9] use an open-data based approach that applies a speed reduction to hazard-exposed roads, which facilitates to calculate the increase in travel time that the population of four case study areas needs under the characteristic hazard scenarios to reach hospitals. Tsang and Scott [43] developed a model that allows to understand the impact of a flooded road network on the accessibility of emergency services. By calculating the traversability of roads under water, based on flood height, parts of the case study area of Alberta in the U.S. are identified, that are affected by a high delay in ambulance arrival time. Another aspect influencing the travel time of emergency vehicles and thus the accessibility to CI facilities, such as hospitals or fire stations, is traffic demand. Data on traffic volume per road segment has been included in previous studies to assess the accessibility of emergency medical services [44–46], however the mentioned studies lack an adaptation of traffic demand to a hazard scenario such as a flood or an earthquake event.

The present study focusses on the identification and quantification of direct access roads from a facility-perspective and proposes a GIS-based model that allows to calculate such access roads based on open source data. To show the applicability of the elaborated model, the accessibility analysis is conducted for two different case studies.

3. Study sites and data

The first case study area is the city of Hamburg in Germany. Hamburg is situated in the northern part of Germany, where it is connected to the North Sea by the river Elbe. With a population of nearly two million inhabitants, it ranks as the second-largest city in Germany [47]. Given its location in the estuarine region of the Elbe and the fact that a significant part of the city is situated on low-lying marshes, storm surges and flooding pose a substantial risk to the city and its inhabitants [48,49]. Hospitals and their access routes are also located in this exposed area, which is why the first case study focusses on the accessibility of hospitals in a storm surge scenario in Hamburg. Fig. 1 shows the locations of the hospitals in Hamburg and the spatial extent of the storm surge hazard.

The model has been designed to be applicable for various locations and types of CI facilities. To achieve this, we used globally and publicly available data. The main input data is the road network from OpenStreetMap (OSM), which includes the basic road network structure and OSM road type classifications. For the locations of the hospitals in Hamburg we used a governmental dataset containing building outlines provided by the ESRI Germany data portal [50]. The considered storm surge hazard covers the flood-prone area in the tidal Elbe area. The data for this scenario is obtained through a geodata server hosted by Hamburg City [51].

As a second case study area, we decided on the metropolitan area of Tehran and Karaj in Iran (Fig. 2). Due to the extensive expansion of the urban area, Tehran is merging with the adjacent city of Karaj [52]. According to the latest available census data from 2016, they collectively have approximately 10 million residents [53]. Tehran is one of the world's most earthquake-prone megacities [54]. The city is situated near multiple active fault lines [55], and statistical calculations indicate the

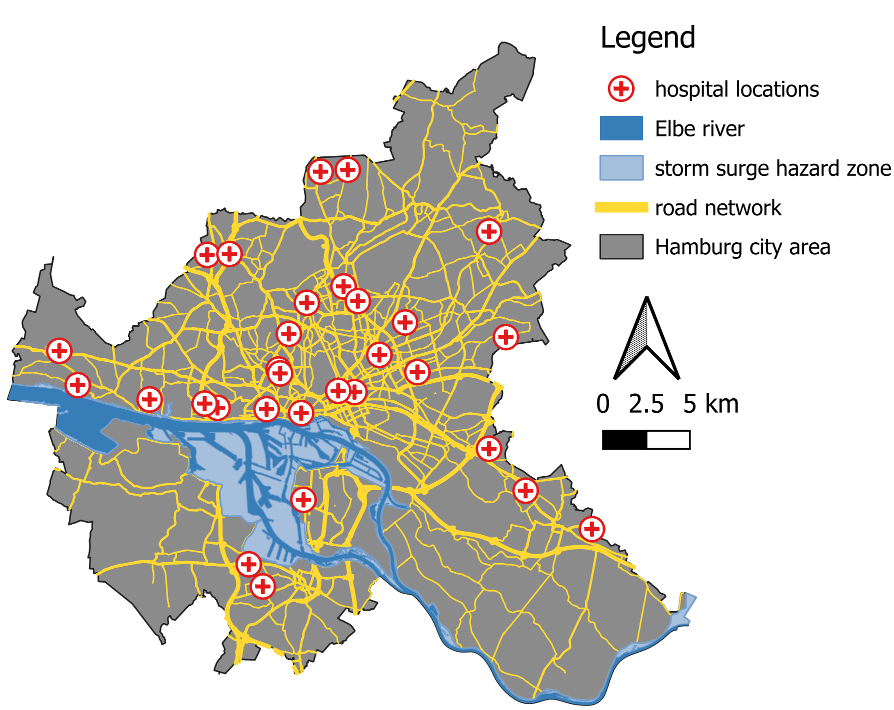

Fig. 1. Map of the case study in Hamburg City.

likelihood of a major earthquake in the near future [56]. In the event of a severe earthquake, collapsed buildings and spreading fires account for the majority of deaths [57,58]. For an effective mitigation of such a disaster, operating and accessible fire stations are indispensable. Therefore, our second case study focusses on the accessibility of fire stations during an earthquake in Tehran-Karaj in Iran.

For the Iranian case study OSM road network data was used. The fire station locations were also retrieved from OSM and combined with a dataset on building footprints provided by Microsoft [59]. The accuracy and completeness of OSM data can vary depending on the region [60, 61]. Therefore, datasets from local authorities should preferably be used if available. Regarding the earthquake hazard considered in the second case study, we determined an earthquake hazard-prone area based on the fault lines elaborated by Kamranzad et al. [55] and adding a buffer zone of approx. 2000 m on both sides of a fault line.

Regarding the choice of study areas for application of the model presented in this study, several aspects need to be mentioned: Hamburg city and the Tehran-Karaj metropolitan region are different by nature and not directly comparable. The main distinguishing aspects of both study areas relevant for the concept of spatial accessibility are number of inhabitants, spatial extent, structure of the road network and local traffic conditions. Being aware of the incomparability of both study areas, the purpose of the present study is to show the transferability of the elaborated model to such diverse case studies and its applicability to different use cases. This aspect is crucial for the further understanding of the study.

4. Model

To address the above-mentioned research gap, we elaborated the Access Road Identification-model (ARI-model). It was initially developed with the software ArcGIS Pro (Version 3.2.1). To provide a free access to the model we decided to rebuild it in QGIS (Version 3.34.0), an open source GIS software. Both GIS have a build-in functionality to connect different tools into a model and let it run automatically to perform the analysis, namely ModelBuilder (ArcGIS Pro) and Model Designer (QGIS). Further information on similarities and differences of both model versions, as well as handling incomplete data, are provided in Section 4.3. The following chapter explains the logic and the functionality of the ARI-model regardless of the used software and the considered scenarios.

4.1. Development of the basic model

On a basic level, the model is able to identify and quantify access roads to CI facilities based on their location and the surrounding road network. The accessibility evaluation requires three types of data, preferably in shapefile format: the road network, the building outlines of CI facilities and the spatial extent of the case study. A principal functionality of the model is to identify access roads based on three different distances to the facility. These buffer distances from the destinations (fires stations, hospitals or else) are manually adjustable to allow customization depending on the specific requirements of the case study. There is no determined value for buffer zones surrounding healthcare facilities in research. Previous studies applying buffer zones around hospitals choose radii depending on the context and use case. Kara and Egresi [62] for example create buffer zones of 1 km and 3 km around each hospital in a densely populated city, arguing that 1 km is a distance that can be covered by walking and 3 km by car or public transport respectively [62]. Another study investigating on healthcare accessibility in Australian cities applies a buffer of 7.5 km surrounding each facility [63]. Considering the spatial extent and the density of facilities in both case studies in the present investigation, a buffer of this size would create multiple overlapping buffer zones and thus generate misleading results. In our approach, the buffer sizes were predefined at 100 m, 500 m and 1000 m, respectively. Setting the minimum buffer to 100 m enables the analysis of roads leading directly to the CI facility. As the roads in the dataset often end at a specific distance to the building, it is important to choose a buffer that is not too close to the facility. To assess the access roads in the periphery of the CI facility, a second buffer is set at 1000 m, ensuring the identified roads maintain their relevancy for direct facility access. An additional third buffer at an intermediate distance of 500 m from the facility provides further explanatory value, particularly if the number of access roads varies significantly between 100 m and 1000 m. Regardless of their specified radii, the generation of these three buffer zones starts from each CI facility's building outline. Taking the center point of a facility to create the buffer could instead lead to buffers reaching into the facility, especially in the case of smaller buffer sizes such as the 100 m buffers. Irregular shapes of building outlines, e.g. if the CI facility is composed of multiple single buildings, are dissolved to one overall facility building outline. This functionality of the model requires each single building outline to have an attribute value specific to the respective facility, e.g. the name of the hospital or the fire station. If the CI facility consists of multiple building outlines that spatially overlap, they are dissolved automatically without requiring further attribute values. In the case of missing building outlines, the point location of each CI facility is used to build the buffer zones and run the analysis. Thus, the location of each CI facility saved as a point feature is the minimum requirement for the model to build the buffer zones and run the consecutive accessibility analysis.

A crucial step to ensure the model's performance lies in filtering only relevant roads. This is based on the consideration that ambulances use only specific types of roads, such as high-capacity roads or roads that hold higher significance for effective urban transportation. As the OSM road network dataset also contains roads like pathways and bicycle lanes it is necessary to exclude these types of roads from the accessibility analysis based on the road type attribute (obtained from OSM). The following road types are considered to be relevant for the accessibility analysis: motorway, trunk, primary, secondary, tertiary, unclassified, service and residential, as well as the corresponding link segments, e.g. primary_link. The performance quality of the ARI-model increases with a correct classification of road types. Possible options for automated tools to check if road types are assigned correctly consist either of machine learning or rule-based approaches (see [64] for more information on existing tools). A detailed investigation on the road classification errors for both study areas is not further addressed, as it is not within the scope of the present study. To detect possible access roads to the CI facility, the model overlaps the road network layer with the three buffer zones. Each intersection of the road network and the boundary of a buffer zone serves as possible access points on a road to the given CI facility. Fig. 3 demonstrates this methodology using a single buffer as an example.

However, not each of these intersection points in fact leads to the CI facility. Dead ends or roads, which cross the buffer but do not lead to the CI facility, are not direct access roads. To eliminate these unconnected roads, a routing analysis is implemented in the ARI-model. By taking the intersections of roads and buffer boundaries as origin points and the respective CI facility as destination point, the model conducts a shortest path analysis. The Dijkstra-algorithm [65] is employed for the routing analysis, a commonly used routing algorithm for shortest path-problems. The crucial point to this routing analysis is that it only uses the road network within the respective buffer to create routes, as the purpose of the model is to find direct access roads within a defined distance to the CI facility.

Fig. 4 schematically illustrates the roads identified by the model as direct access roads in contrast to those that are not. In this example, from a potential of 12 access roads to the CI facility, only nine remain as direct access roads. The ARI-model conducts this iterative routing analysis for each of the three buffer zones to quantify the number of access roads leading to each CI facility in the study area.

The described process is applicable for scenarios where the CI facility is the destination of the routing calculation, like in the case of hospitals.

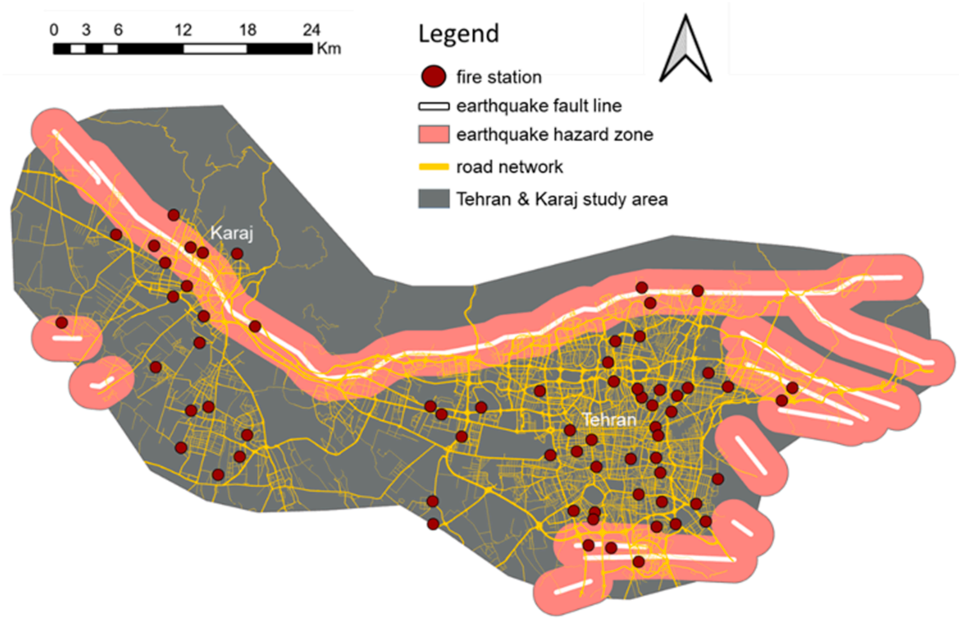

Fig. 2. Map of the case study in Tehran-Karaj metropolitan region.

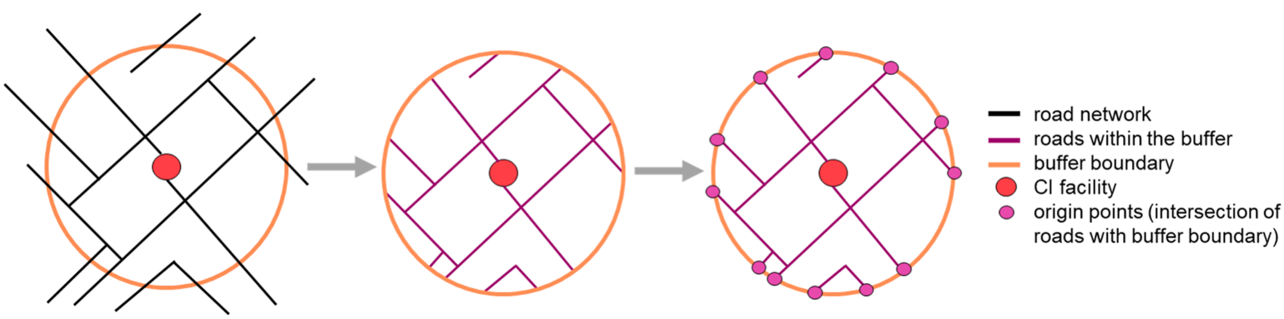

Fig. 3. Identification of possible access roads by intersecting the road network with the boundary of the buffer (schematic overview).

However, alternative applications may require reverse routing. In the case of fire stations emergency responders have to drive to the surrounding area, away from the facility. In practical terms, assessing the connectivity of a fire station to the road network is of greater importance than assessing its accessibility. Consequently, the model is designed to work bidirectional, treating the CI facility as the origin and the intersection of roads with buffer boundaries as destination points. Given the need for bidirectional access during emergency response, one-way roads are not considered in the model. For simplification purposes, the term of connectivity in case of the fire stations is referred to as accessibility in the remaining of the study.

4.2. Combination of the model with a hazard map

How the accessibility of CI facilities changes when facing an imminent hazard, such as a flood or an earthquake, is of great interest for emergency management. Therefore, the second part of the model consists of evaluating the spatial accessibility of CI facilities during a hazard scenario. Regarding the data, the model requires a hazard map containing the spatial extent of the hazard under study. For use cases where the area under study differs from governmental boundaries or is defined through manual selection, the model automatically clips the hazard map to the study area. CI facilities located within the hazard zone are excluded from the routing analysis and are deemed inaccessible if directly affected by the hazard. Similarly, origin points located within the hazard zone are eliminated and do not serve as origin points for the analysis. Roads, which overlay with the hazard zone are viewed as not traversable anymore and are likewise excluded from the routing analysis. The adjusted datasets are used for a second run of the ARI-model, this time with the hazard scenario included. Similar to the basic model a shortest path analysis allows detecting the absolute number of access roads to the facility in a hazard scenario.

The peculiarities when conducting the routing analysis in a hazard scenario are schematically shown in Fig. 5. As starting point no. 1 lies within the hazard zone, it is eliminated as a possible origin point. Although points no. 2 and 3 initially count as origin points for possible access roads, no direct route to the CI facility can be found due to the hazard zone in between. As a consequence, the nine access roads exemplary identified in the baseline scenario (Fig. 4) decrease to six direct access roads in a hazard scenario, indicating a reduced accessibility of the CI facility (Fig. 5).

Fig. 6 shows an exemplary application to a selected hospital in the case study of Hamburg in the baseline scenario. The three buffer zones are visualized as well as the origin points for the routing analysis. If the routing algorithm finds a possible route between an origin point and the facility to reach, it is detected as access road to the CI facility. In the map below the southernmost origin point at a distance of 500 m from the facility serves as an example for a possible origin point where no route to the CI can be found. Equally to the given example, the routing is conducted for each CI facility in the respective use case.

As many hazards are not static but dynamic events, a possible application of the ARI-model to dynamic hazard scenarios needs to be

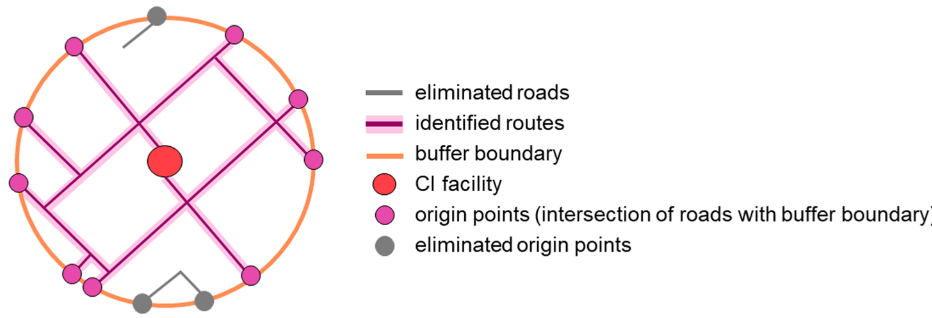

Fig. 4. Direct access roads after running the shortest path analysis (schematic overview).

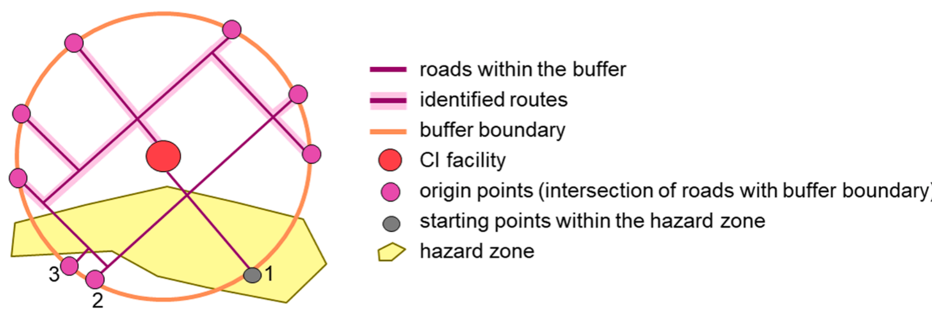

Fig. 5. Identified access roads in a hazard scenario (schematic overview).

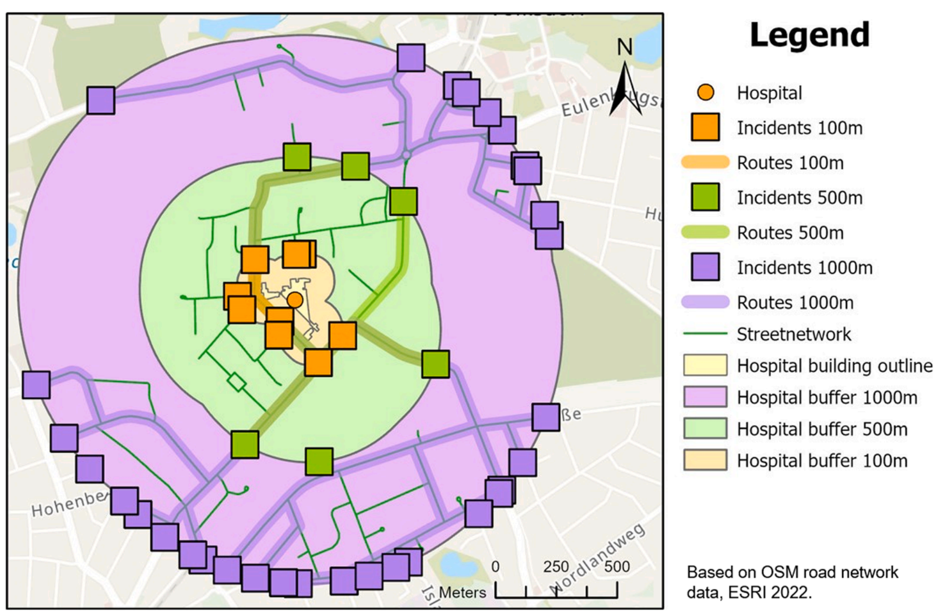

Fig. 6. Exemplary application of the ARI-model to a selected hospital in Hamburg.

explained. Time-varying hazards are not modeled explicitly but the model is adaptable to dynamic hazards if time-varying hazard maps can be provided accordingly. To account for dynamic hazard scenarios, and thus temporarily impassable roads, the input data on the hazard extent needs to be modified and adapted to the changing hazard scenario. Applying the model to different times in a flood event, e.g. in an hourly time interval, can provide different results and allow a direct comparison of the effects of the hazard on access roads and accessibility of CI facilities.

4.3. Comparison of ArcGIS and QGIS model versions

In this subsection, both model versions in ArcGIS Pro and QGIS are compared with each other by explaining concrete similarities and differences. With regard to the similarities, the following tasks are equally addressed by a sequence of tools: selecting only relevant road types, creating buffer zones based either on building outlines or point locations of CI facilities and intersecting the road network with the buffer zones for the subsequent routing analysis. The differences of both model versions are visible in the routing part: the ArcGIS Pro model version requires several single tools preceding the routing, e.g. the "Create Network Dataset" tool creates a folder to save the routing network, the

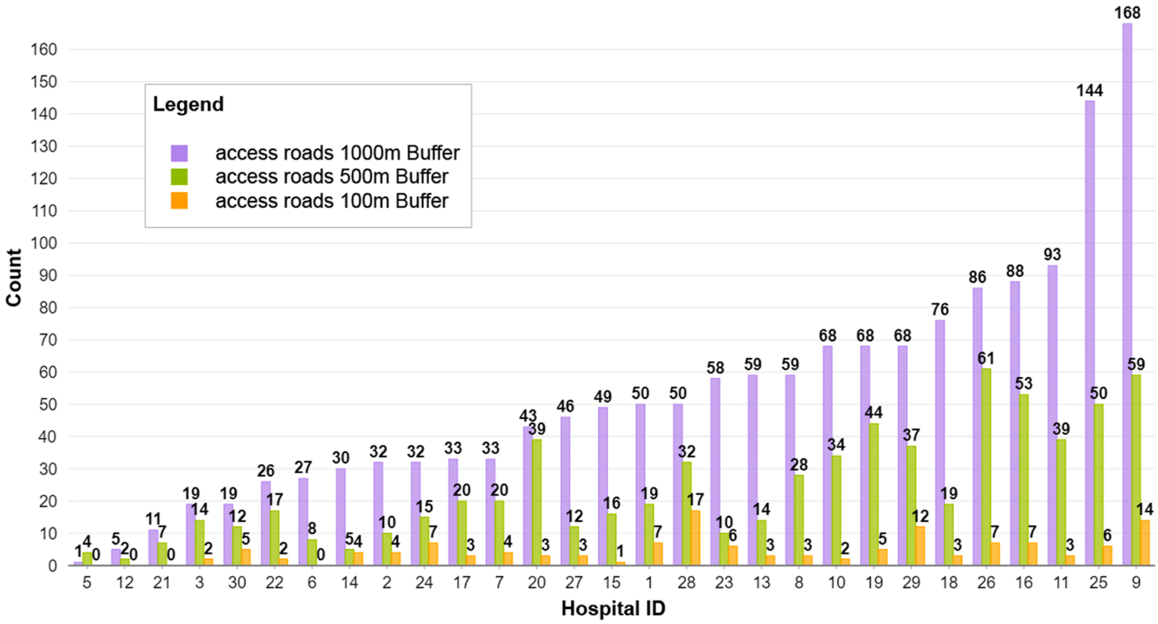

Fig. 7. Absolute number of access roads per hospital for Hamburg.

"Build Network Dataset" turns the road network dataset into a routable network, the locations of the facilities and the intersection points are declared specifically as destination and origin points by the "Create Locations" tool. In QGIS all these inputs are combined in the "OD matrix from Layers as Lines m:n" tool. In short, in ArcGIS Pro the input data is created along the execution of single tools, whereas in the QGIS version of the model the input data is defined at the beginning and referred to at later stages of the model. Regarding the combination of the model with a hazard map, ArcGIS Pro allows to include the respective hazard extent as a polygon barrier in the routing analysis. In QGIS however, a work-around is needed by intersecting the road network with the hazard extent and excluding roads within the hazard zone prior to the routing analysis. In summary, both model versions are able to create the desired output, but vary in timing of input data definition and concrete tool execution.

Another important aspect to point out when comparing the performance of both model versions is the handling of incomplete road network data. Although the OSM road network data can be assumed of sufficient quality for routing analyses in the case of Germany [66], incomplete road network data in other regions can influence the results of the ARI-model. Both versions of the model are adjusted to continue with the routing analysis, even if a facility is not reachable by the underlying road network. This prevents the model from stopping the analysis due to poor data coverage. Examining the visualization of the routing results afterwards to check which facilities could not be reached at all helps to identify areas where road network data is missing and should be improved by considering additional data sources.

5. Results

5.1. *Accessibility of hospitals in Hamburg, Germany*

In the city of Hamburg there are 30 hospitals from which 29 were considered in the accessibility analysis. One hospital was not in the area covered by the road network dataset, which is why it was discarded by the routing algorithm. In terms of the absolute number of access roads for hospitals in the city of Hamburg there are considerable disparities along the respective facilities (see Fig. 7).

Without any hazard influencing the access to the hospitals, hospital no. 5 is the hospital with the least number of access roads across the city. On the contrary, hospital no. 9 has a total of 241 access roads of which 168 are in a distance to 1000 m to the hospital, 59 in a distance of 500 m and 14 in a distance of 100 m. This hospital is located in the city center where a higher road density can be observed (Fig. 1).

The results indicate an impact of storm surges on the accessibility of hospitals in Hamburg. Out of 29 hospitals, nine hospitals lose access roads due to the hazard. In Fig. 8 the orange line represents the average number of access roads in the baseline scenario, whereas the blue dotted line shows the average number of access roads in a storm surge scenario respectively. In a distance of 100 m and 500 m from the hospital, the number of access roads barely changes and the values only vary in decimals. In a 1000 m distance the average number of access roads decreases by almost one from 53.14 access roads in the baseline scenario to 52.17 access roads in the storm surge scenario showing a slight impact. Comparing these results with the locations of the hospitals in the city and their distance to the storm surge hazard (Fig. 1), 20 out of 29 hospitals are >1000 m away from the hazard zone, which explains why their identified access roads are not affected by the storm surge. The number of remaining access roads in the hazard scenario relates directly to the term "robust component", a concept in graph theory indicating the remaining edges in a network to reach certain destinations [67].

Fig. 9 shows the importance of considering not only the absolute loss of access roads but to focus on the relative share. Hospital no. 28 loses a total of 15 access roads across all three buffer zones due to the storm surge hazard. As this hospital has a total of 99 access roads, the storm surge causes the loss of about 15 % of its access roads. Instead, hospital no. 5, which already stood out by having a total of five access roads and therefore the least in the whole study area, loses two access roads due to the hazard, which are 40 % of its access roads. Speaking in relative terms, the accessibility of hospital no. 5 is therefore the most affected in the case study. These two examples highlight the significance of the relative value of access road loss and shows that a storm surge in Hamburg can indeed have a high impact on certain hospitals, which can be efficiently identified by the model.

5.2. *Accessibility of fire stations in Tehran and Karaj, Iran*

For the case study in the Tehran-Karaj metropolitan region in Iran, a total of 68 fire stations were considered in the model. One fire station was not reachable via the road network, which is why no access roads

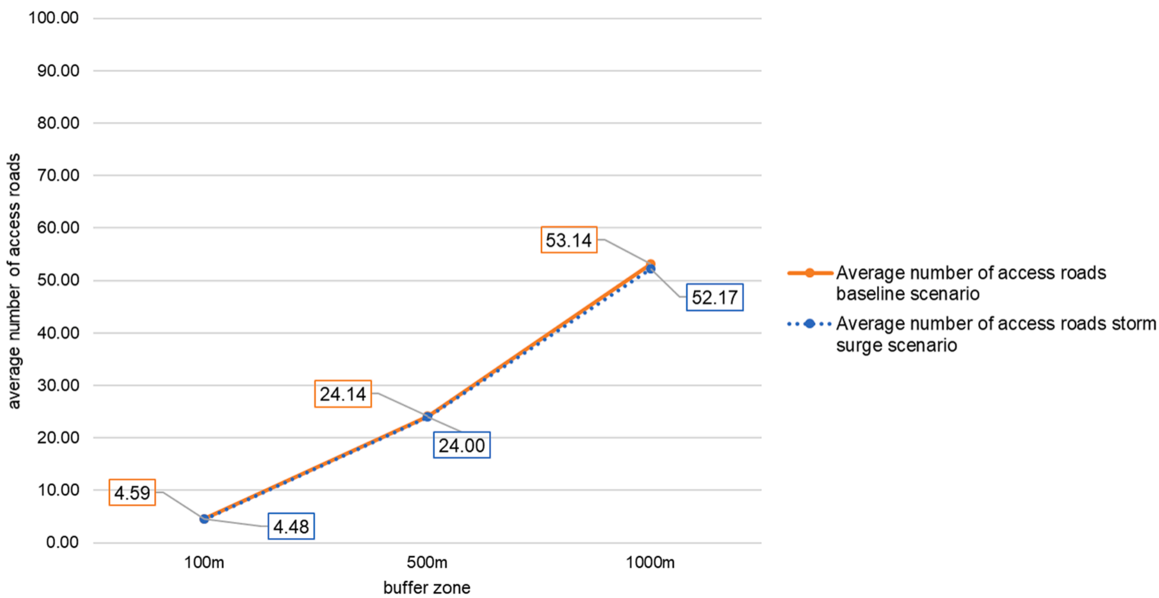

Fig. 8. Average number of access roads per buffer zone for hospitals in Hamburg.

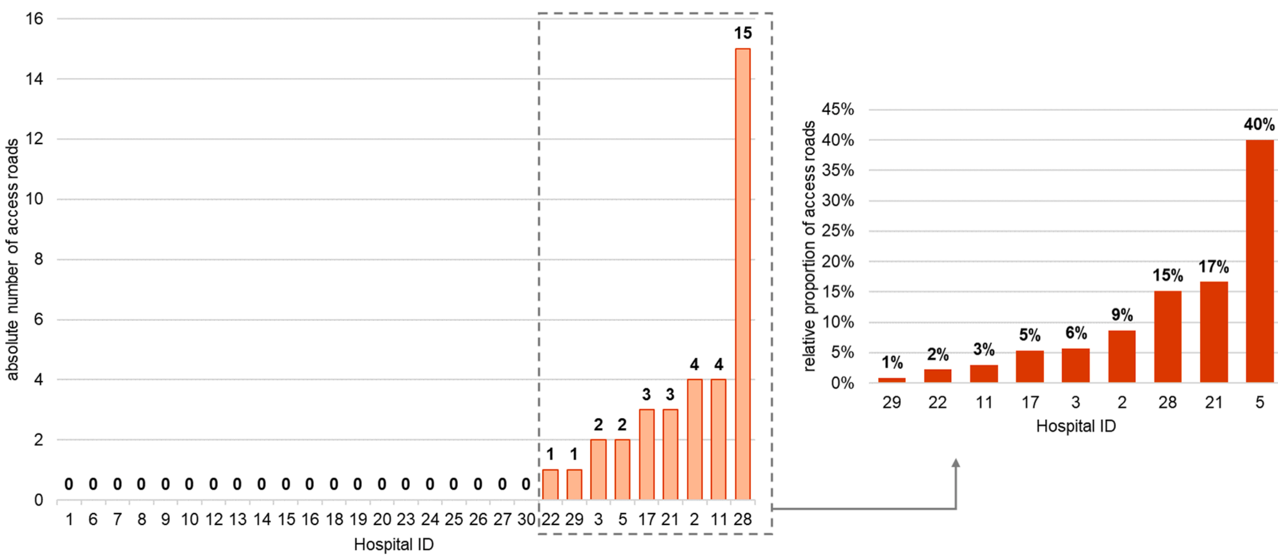

Fig. 9. Comparison of absolute and relative loss of access roads for hospitals in Hamburg due to a storm surge hazard.

could be identified for that facility. The facility with the lowest number of access roads is facility no. 48 with 19 access roads in total. For fire station no. 59 the most access roads were found; a total of 385 roads. The number of access roads in the 100 m buffer zone range from one to 13 and in a distance of 500 m from eight to 99. For the 1000 m buffer zone the number of access roads shows the greatest variance, ranging from 19 to 385 (see Fig. 10).

The amount of access roads to fire stations for the region of Tehran-Karaj reflects the dense urban structure and road density of the study area. In average, fire stations in the Iranian case study region have 4.84 access roads in a distance of 100 m from the facility. In case of the portrayed earthquake hazard along the fault lines, the number of access roads in a perimeter of 100 m to the facility is reduced by one on average. This value increases with the buffer distance: 500 m from the facility the average number of access roads shrinks by 6.26 and in a distance of 1000 m by an average of 16.22 access roads per facility (Fig. 11).

About 62 % of the fire stations in Tehran-Karaj do not lose access roads as they are located outside of the potential earthquake hazard zone. The other 38 % of the fire stations whose access roads are exposed to an earthquake are represented in Fig. 12. 17 of them lose more than half of their access roads due to the earthquake and four of them lose all their access roads. The most affected fire stations in terms of their accessibility are therefore no. 65, 36, 44 and 15. In the case of the proposed earthquake scenario, all of their access roads are assumed to be affected by the hazard and thus the facilities are completely inaccessible or rather lose their connection to the surrounding road network completely.

5.3. Practical implications of the results

In this subsection we describe the explanatory value of quantifying direct access roads to CI facilities and its added value to existing accessibility analyses. The ARI-model is able to calculate the relative share of direct access roads per facility that are exposed to a hazard (see Fig. 9). This information allows to point out which facilities are in a

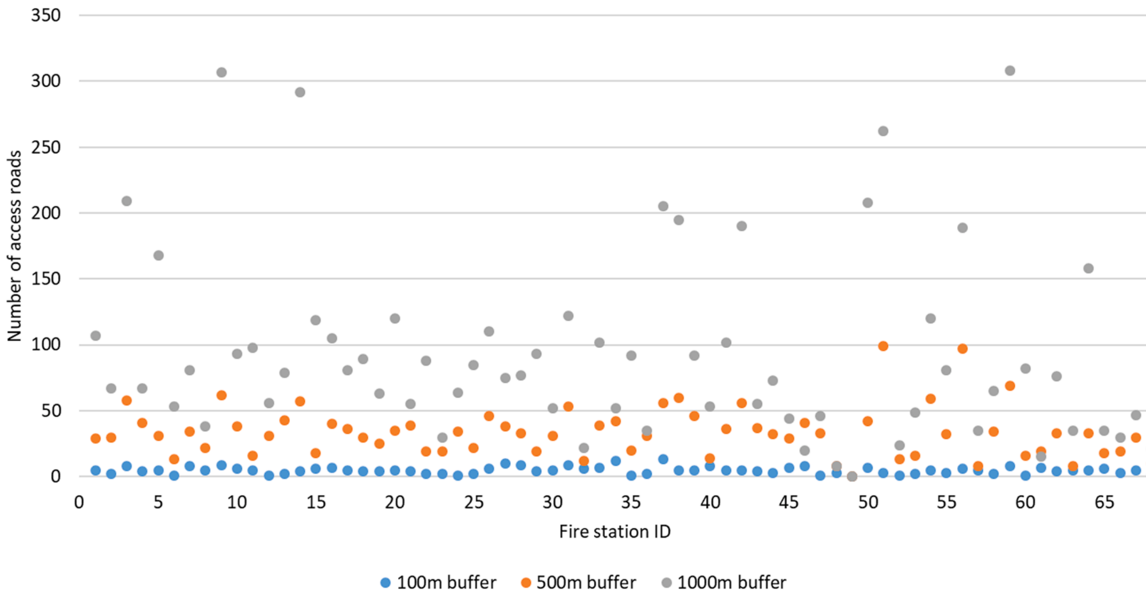

Fig. 10. Absolute number of access roads per buffer zone for fire stations in Tehran and Karaj.

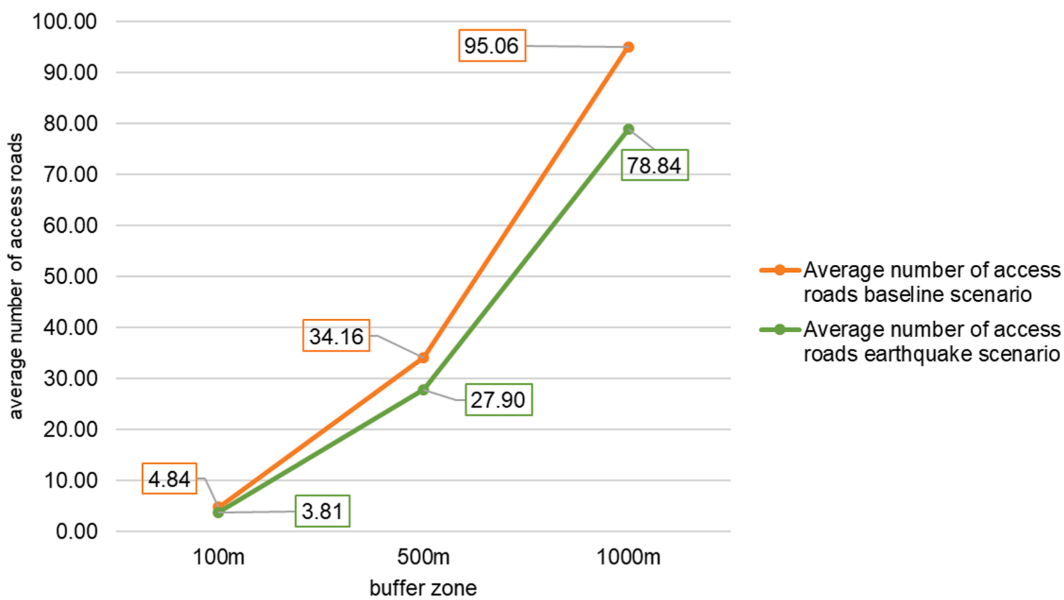

Fig. 11. Average number of access roads per buffer zone for fire stations in Tehran/Karaj.

higher risk of overall accessibility loss. The relative share of exposed access roads describes a value of redundancy of accessibility. We further explain this connection with the following example: If 100 % of the direct access roads of a facility are exposed to the hazard, no redundant access roads are available (e.g. fire station no. 15 in the case study of Tehran-Karaj). Opposed to this example, a facility with about 10 % exposed access roads still can be reached by 90 % of its remaining direct access roads (e.g. fire station no. 11). This information can be more relevant than an absolute value for the loss of access roads, as it quantifies the available redundancy to reach a facility in case of a hazard. Furthermore, loosing two access roads might not seem as a considerable impact at first, but if the facility is only accessible via four roads in its near perimeter, the loss of two access roads can lead to major impact on the facility. This information is provided by the ARI-model and can be valuable for stakeholders of emergency management, such as first responders and emergency coordination centers.

In regard to the application of the model to both case studies, possible practical implications that follow from the results are: In the Tehran-Karaj region, emergency management stakeholders should check the supply and demand ratio for inaccessible fire stations (fire station no. 15, 36, 44 and 65) and if the population can be served by surrounding facilities that are still accessible. The same applies to facilities that are heavily restricted in their accessibility (>80 % of exposed access roads), as a substantial restriction in their ability to provide emergency rescue services can be assumed. Similarly, for the case study in Hamburg city, a closer inspection on hospital 5 is advisable. A loss of 40 % of its direct access roads can have an effect on the hospital's functionality of serving the surrounding population. Thus, the supply catchment area of the hospital should be checked carefully and resources should be relocated in case of a flood hazard if necessary.

6. Discussion

The results show that the ARI-model has the means to provide an overview of the road-based access redundancies for CI facilities, and how spatial accessibility changes under different hazard scenarios. This approach focuses on the CI facilities rather than the served population and therefore enables to prioritize facilities, which are especially threatened. The two very diverse case studies show the transferability of the model and how the severity of the impact is dependent on the hazard and road network. Several options for improving the ARI-model in the future are presented in the discussion, most notably the inclusion of weights for the different input parameters.

6.1. Case study comparison

As mentioned before, the results of both case studies are not directly comparable due to different characteristics of the chosen urban systems. Nonetheless,in this subsection we want to highlight the different results that can be reproduced by the ARI-model depending on its concrete application case. As different hazard types were examined in this paper, two main aspects have to be considered when interpreting the results of the case studies: First, the spatial extent of the hazard depends highly on the hazard type and the study area. The storm surge hazard unfolds near to the river Elbe while the impact of the earthquake hazard mainly strikes near the fault lines. In the Tehran-Karaj case study, several CI facilities and their respective buffer zones lie completely within the hazard zone, which is why they lost all of their identified access roads (Fig. 12). In the Hamburg case study, only nine out of 29 hospitals are affected by the loss of access roads and the most affected CI facility loses about 40 % of its access roads (Fig. 9). Given the considered storm surge scenario, all hospitals in Hamburg are still accessible. Secondly, the impact on the road network differs between the two hazards. If a road exposed to a storm surge is still passable depends on secondary factors like e.g. flood depth, run-off capacity or the willingness to take risks of the driver. Instead, a road affected by an earthquake often experiences direct structural damage or is blocked by collapsed buildings and is either passable or not. Furthermore, the different results of the ARI-model in accordance to the total number of access roads per buffer zone stress the disparities in road network structure of both case studies. Nonetheless, applying the ARI-model to two different case studies showed its transferability and adaptability to different hazard types and CI facility types.

6.2. Model limitations and future improvements

The buffers in the present study were set to 100 m, 500 m and 1000 m due to the reasons stated before. For other case study scenarios, the model can easily be adjusted by choosing different buffer sizes or adding more buffers if necessary. We are aware of the fact that different sizes of the buffer zones lead to different results. However, the explanatory value of the ARI-model focusses on the relative comparison of the accessibility between the CI facilities in a study area and how it changes when facing an ongoing hazard such as a flood or an earthquake, as shown in this paper. Nonetheless, limiting the road network to a pre-defined perimeter around each CI facility is an assumption that requires thorough justification, as road network redundancies might be overlooked. First, the model includes a functionality to adjust the buffer size in relation to the specific case study. If a larger area is of interest, the model can be adapted accordingly. Secondly, and most importantly, the aim of the ARI-model is to identify direct access roads to facilities instead of investigating the overall redundancy of the road network. The latter has been addressed extensively by previous research, both in baseline and varying hazard scenarios [68–71].

On a methodological level, the ARI-model has room for improvement in future studies. When CI facilities are closer than 2000 m to each other, the constructed buffer zones overlap, which can lead to incorrect results. In the Tehran-Karaj case study this was the case for fire station no. 59. In a distance of 1000 m to the facility, only 248 access roads should have been identified instead of 304. This can occur in highly build-up zones with a dense road network, as it is the case for the Iranian study area. A possible approach to mitigate this could be to include an iteration when building the routes to the facilities, which would come with the downside of longer calculation time. Another limitation of the study is the data quality of OSM road network data and data on CI. Especially in the case of the Iranian fire stations it was not possible to validate the data as CI names are written in Persian language. For the case study in Hamburg, it was feasible to validate the names and locations of the hospitals with Google Maps. However, the aim of the present study is to describe the general possibilities of conducting an accessibility analysis

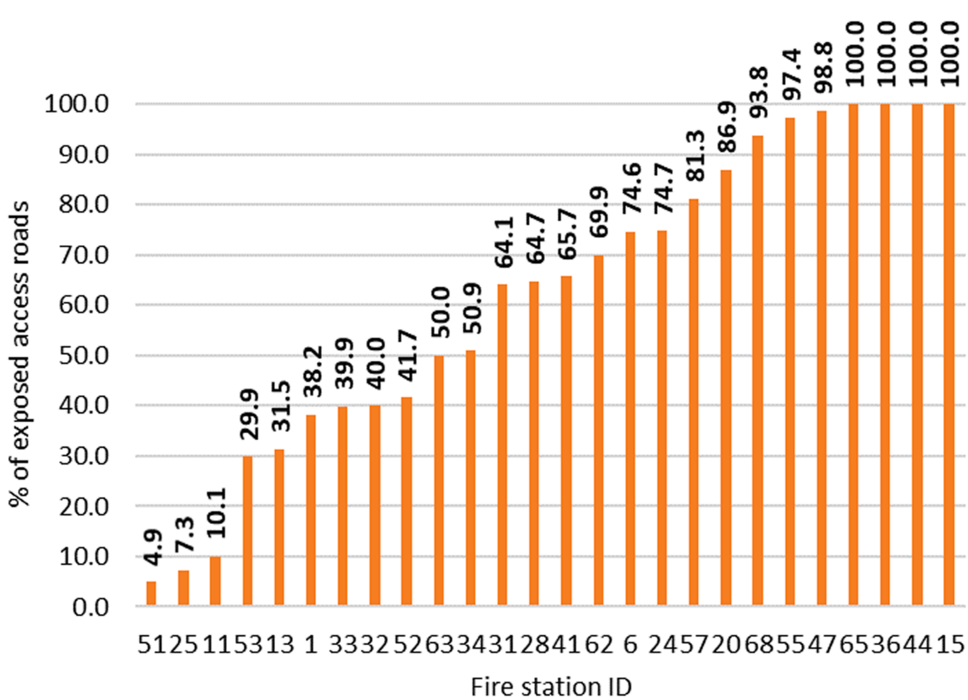

Fig. 12. Relative share of exposed access roads to an earthquake hazard in Tehran/Karaj.

with open source data and present the general transferability of the approach.

Another major idea for improvement of the ARI-model is to adapt from a distance-based to a time-based measurement of accessibility. Time is a more adequate measure for accessibility than distance [72], especially in the context of buildings and locations that need to be reached in a given time like hospitals. In this regard, including factors restricting driving speed into the model like flood depth or traffic demand seems appropriate. On the one hand, these considerations would improve the applicability in reality and lead to results that are more realistic. On the other hand, modeling traffic demand during a hazard is a highly complex process and the dynamic properties of traffic and flood hazard propagation have to be considered. In accordance to previous studies focusing on the vulnerability of road networks to seismic hazards [36], another possible option for improvement of the ARI-model would be to include data on building heights within the buffer zones to examine if single road segments are affected by collapsed buildings. This would leverage the status of road segments from being exposed to the earthquake hazard to being affected by it or in this case its cascading effects. Also information on fragility curves for road segments would improve the analysis to provide additional information on the road damage status, as shown in previous studies [73].

6.3. Weighting options for road-based CI accessibility

Weighting is a crucial part of modeling, with a high potential to improve the results and provide further insights if applied correctly. In the elaborated ARI-model weighting is not included, which leaves room for further improvement. Models like the ARI-model, that focus on road-based CI accessibility and strive to prioritize affected CI for pre-disaster protection measures, profit from the inclusion of three weighting components: The served population, the road specifications and the capacity of the CI facility. If further information to these components are available, their inclusion can lead to a more valid prioritization of CI protection measures. Based on other research, we want to discuss possible weighting options and how to include these weights in a future version of our model.

The amount of served population by one CI facility is often part of a criticality assessment, following the thought, that facilities, which provide service to more people have a higher relevance and lead to more damages and fatalities if they fail [74]. Similarly, it can be argued, that a hospital or a fire station, that has more people in their direct vicinity, either because of high population density or few alternative facilities, are more important than others. The most common version to implement this weighting component is to calculate routing-based catchment areas of the CI facilities and calculate population numbers based on census data [75,76]. One step further might include a social vulnerability assessment of the respective population to get insights in demand variations of different population groups [42,77]. Alternatively, more specific data, like emergency calls for fire and rescue services [22] or patient statistics of hospitals can be implemented. As data on global population density is publicly available, the first method can be implemented with relative ease. However, the two other versions require more specific data that is often difficult to obtain. A further challenge arises, if the weighting is needed for a comparison between normal and disaster state, since it is often difficult to calculate scenario specific numbers that accurately represent the rising demand of CI services during a disaster.

The specifications of a road can have a high influence on the accessibility. Type and construction material can influence the physical vulnerability of a road to a disaster, which can lead to more destruction in different road classes. Some road types also have a higher vehicle capacity and a higher load endurance. In the case of a hospital evacuation for example, it can be crucial to have several broad roads to provide room for assembly areas for ambulances and robust roads so they can endure the high load of multiple heavy trucks. Several metrics to weight road relevance are used in research. Road-length can be an interesting indicator for large study areas, since it can be connected to travel time, if that is not yet included. For smaller calculation areas like in the case of the ARI-model, road length as weighting indicator would not be suitable as the routing is only applied to relatively small buffer zones. Therefore, no significant differences in road length or travel time can be expected. Road type as a weighting factor is more common, due to the previously mentioned reasons. Here, however, the precise balancing of the weighting is challenging, since road type is a categorical indicator and therefore needs manually assigned weights to each road type, which increases chance of bias. Auxiliary data like road width, number of lanes or average speed [78] can help in this regard. If the direct disaster impact on the road network should be included into the weighting, then indicators like road building type and materials [79] or flood depth for vehicle traversability [80,43] are important factors.

The capacity of a CI facility, here refered to as the amount of people in need a facility can serve, also has influence on its prioritization. The reduction of accessibility to a main hospital for example could result in more negative outcomes, than the total loss of accessibility to a very small hospital. To specify this impact, CI capacities can be used as weighting. These capacities differ for each CI type. While the number of beds is a common indicator for hospital relevance [40,81,82], other possible indicators like hospital specializations (e.g. burn unit, trauma centers) or physical vulnerability in combination with disaster exposure are less used, but still relevant indicators. For fire or ambulance stations, weighting indicators could be the number of vehicles, the number of staff or available doctors or specialized equipment. As mentioned above, categorical values and data availability can pose a challenge here as well.

For the ARI-model, we plan to include all three weighting components in the future. While this will lead to a more realistic result, it comes at the price of lower transferability, since case study and CI specific data are used. For the hospital case study of Hamburg, "served population" could be used for a driving time-based catchment area calculation, based on ambulance driving speeds used in [22]. In terms of „road specifications" a linear weighting of the OSM road types according to [78] could be possible, even though, a weighting method that takes road width and load capacity directly into account would be preferable. For the hospital capacity, we would choose the yearly number of treatments, which are available via the Klinik-Atlas [83], a governmental overview of hospitals in Germany. A first approach of weighting would treat the three weighting factors equally, which could later be updated by assigning weights to the weighting factors based on for example expert opinions.

6.4. Practical application of the ARI-model

As a decision support tool, the ARI-model can provide valuable information for stakeholders of disaster risk management or urban planning. For example, when deciding on possible locations for additional facilities in an area, e.g. building healthcare facilities to compensate for a risen patient demand, the results of the ARI-model can serve as an additional input to conventional location-allocation studies. Typically, location-allocation studies aim at determining optimal locations for additional facilities based on factors such as minimizing travel costs, proximity to main roads, or maximizing coverage [84–86]. In a hazard scenario, information on the affectedness of direct access roads to future infrastructure facilities obtained by the ARI-model can serve as additional input for decision-making in location-allocation problems. The application of the model to the two case studies showed that the loss of direct access roads due to a hazard can affect the accessibility of the given facility, which in turn has to be considered in the planning of future CI facilities.

Previous studies argue that the payoff to invest in preventive measures that increase the resiliency of a city or a community might not be recognized by relevant stakeholders [87]. By applying the ARI-model to a given study area, the loss of access roads due to a spatially distributed hazard can be directly visualized. This enables stakeholders of urban planning or emergency management to plan preventive measures more precisely and prepare for possible accessibility loss of single CI facilities. Furthermore, the developed model can be helpful to enhance the risk awareness of the local civil protection and CI operators, especially in cities or regions that have not experienced major hazards before [87].

Regarding the application of the ARI-model in direct disaster response, data on the spatial extent of the ongoing hazard is required. Combined with remote sensing data of natural hazards, the ARI-model can be helpful to increase situation awareness and provide valuable information for emergency management services to understand where facilities are suffering potential loss of access roads and provides a basis for rerouting vehicles accordingly. In order to prioritize the evacuation of CI facilities, such as hospitals, and enhance the decision-making process, additional information on the hospital's capacity would be necessary. Nonetheless, the ARI-model represents a useful decision-making tool and adds valuable information regarding CI facility access to existing tools and methods.

7. Conclusion

We presented an automated GIS-model, which is able to identify direct access roads to CI facilities and to quantify accessibility loss due to different hazard impacts. A main feature of the model is its functionality to calculate access roads across several different distances to the specific CI facility. By applying the ARI-model to the case studies in Hamburg, Germany and in Tehran-Karaj, Iran, the transferability of the model to different use cases was shown. For the case of Hamburg City, a possible storm surge hazard showed a low impact on the overall accessibility of hospitals as two-thirds of the facilities are not in near vicinity to the hazard zone. Nevertheless, a loss of up to 40 % of access roads was detected for single hospitals. In Tehran-Karaj the assumed earthquake hazard reduces the accessibility of fire stations considerably, as a fifth of all fire stations in the case study lose more than half of their access roads, of which four facilities are completely inaccessible due to the earthquake hazard.

To increase the applicability of the ARI-model in reality, we propose several aspects to address in future studies: As natural hazards are highly dynamic, implementing a dynamic component into the model seems appropriate. This could leverage the ARI-model to consider temporarily closed roads, which is especially relevant in case of hazards whose extent and impact changes over time, such as flood events. Including more detailed data of the hazard, e.g. flood depth or data on seismic microzonation, can lead to more accurate results of the model. With detailed information on a road segment level, it would be possible to model the temporal availability of roads by considering them as closed, if a specific flood depth threshold is surpassed. The static approach presented in this study also does not consider traffic demand as an additional factor influencing accessibility. As time is a more relevant measure for accessibility than distance, the idea is to adapt the ARI-model to a time-dependent fastest path analysis. Additionally, the model would benefit from improvements in quality of the data used. Regardless from its multiple advantages of availability and usability, open source data is subjective to data quality issues. The ARI-model relies on OSM road network data and coupling this data source with existing tools for detecting road classification errors could leverage the quality of the overall output of the model. With respect to overlapping buffer zones due to the proximity of different CI facilities, we propose the option to include an iterative functionality in the model, that conducts the shortest path analysis for each facility individually. We recommend to tackle this issue in future versions of the model to avoid misleading results. We further discuss several weighting options for the input parameters that can further enhance the results. It is planned in the future to include the served population, the road specifications and a capacity indicator for the respective CI as weights into the ARI-model. Lastly, we recommend on elaborating a meaningful and efficient option to validate the results of the model with data of real-life scenarios or data of blocked roads around single CI facilities.

The presented ARI-model allows identifying CI facilities that are potentially limited in their accessibility by local hazards. Since the routing part of the model is based on OSM data, it can be applied globally and regardless of the CI facility type or the hazard type. Furthermore, it allows prioritizing CI facilities according to their degree of access inhibition in disaster situations. This information is crucial for emergency management and can be used by decision makers to effectively prepare countermeasures for the affected CI facilities and the respective road network before a possible disaster hits, or to prioritize resources during disasters.

CRediT authorship contribution statement

Ana Maria Mager Pozo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Priesmeier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Alexander Fekete:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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