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Developing a spatial solution for earthquake crisis management using volunteered geographic information and genetic algorithm: A case study of an earthquake, Tehran, Iran

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ABSTRACT

Natural disasters, such as floods and earthquakes, affect societies more than people think. These effects range from economic effects to social harms and casualties. An earthquake may only last a few seconds, but its damage lasts for years. The purpose of this study is to collect volunteered geographic information from people in the affected areas using smartphones and to identify areas of high priority for relief using the collected data. Then, spatial analysis enables us to assess the condition of the road network after the earthquake and determine the degree of damage due to debris. Ultimately, using the genetic algorithm, the process of assigning rescuers to crisis points and routing is done considering the extent of road damage. The case study is district 2 of Tehran. In this paper, it will be shown that a mobile information system is necessary to fill the gap between the people, the crisis headquarters, and the relief teams. Such systems collect crisis-related data with the help of people in crisis areas and help headquarters and relief decisions to be faster and better. The results indicate a high vulnerability of roads in most areas of district 2 of Tehran. Eventually, about 243.5 km of the region's roads, which also make up a quarter of the region's vital arteries, are damaged by at least 80% that makes the relief process difficult.

KEYWORDS

Natural disasters
Rescue operations
Vulnerable roads
Geocrowdsourcing
Mobile application
Genetic algorithm.

1. Introduction

Iran is one of the countries with high intensity of earthquakes. The main reason for this matter is the location of Iran between three main plates namely: Arabian plate at the Southwest, Indian plate at the East and Southeast, and Siberian plate at the Northeast (Zare & Kamran Zad, 2015). Unknown risk, inappropriate disaster management, high exposure of elements at risk, and vulnerable buildings are four major factors that can lead to increased casualties and loss of property in earthquake events (Hassanzadeh et al., 2013). For example, the Bam city earthquake in Iran (2003) resulted in the death of more than 30,000 people and the destruction of infrastructures and many buildings, because the seismic risk at Bam city was under-estimated (Nadim et al., 2004), and there was no plan for disaster management (Alavi Razavi, 2008).

That's why, disaster preparedness and community resilience stand crucial from the standpoint of reducing disaster risks (Zutshi et al., 2019). Given the probability of highly dangerous future events, risk estimation should be given focus by using the limited and freely available data to predict future vulnerable scenarios of an area that observe the involved uncertainty in the analysis (Jena & Pradhan, 2020). Thus, joint analyses of building damage and evacuation flows along the evacuation paths become essential to determine the risk levels for the urban scenario and to provide risk mitigation solutions (Bernardini & Ferreira, 2020).

With the fast development of mobile Web and computing technologies, as well as the increasing availability of mobile devices, mobile information technologies have revolutionary influence the human society (Gao & Mai, 2017). In the

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domain of Geographic Information Systems (GIS), advanced mobile information technologies have lowered the traditional enterprise GIS fence and enabled a variety of novel applications which can help improved positioning and tracking accuracy, efficient field data collection, ground truth validation, location intelligence, decision support, etc. (Lemmens, 2011; Abdalla, 2016). The revolution brought by this new trend has been traditionally associated with the term Volunteered Geographic Information (VGI), that Goodchild coined and explained by comparing humans to ''intelligent, mobile sensors'' able to acquire precious geospatial information of unparalleled depth in both a spatial dimension and a temporal dimension (Goodchild, 2007). Another successful term that is widely used in GIS literature is geocrowdsourcing (Goetz & Zipf, 2013) or simply crowdsourcing (Hudson-Smith et al., 2009; Geng et al., 2016) involving the collection of geospatial information performed by an undefined network of people. However, even though VGI and crowdsourcing have slightly different underlying meanings, they are usually treated as synonyms or even combined (Peterson, 2013).

The focus of this article is on creating an internet connection and collecting data from the critical area by amateurs who voluntarily participate in this activity using their mobile phones. Mobile phones have played an important role in shaping technological innovations. They connect directly to the Internet, and not only the GNSS receiver but also a large number of other sensors allow them to easily access and share spatial content, as a result, they provide the basis for many VGI and collaborative assessment activities. After determining the points with high priority of relief, the degree of damage to the roads is estimated and at the end, the process of allocating and finding the best route to these points is done.

The specific objectives of this research can be divided into the following three categories:

- Timely response to the needs of the victims in the field of relief by identifying high-risk areas before the earthquake crisis and reducing the arrival time of rescue forces by moving in predetermined optimal routes;
- Performing routing operations during the mission, taking into account routing preferences and making navigation decisions before reaching the target points;
- Finding survivors in need of rescue by getting short but accurate reports sent through the application;

2. Study Area and Datasets

In this study, in order to determine the vulnerability of roads in the area, the existing vulnerability map of buildings in the study area is used. To produce this map several criteria (distance from the fault, Peak Ground Acceleration or PGA, number of floors, and type of structure) were combined.

As is shown in Figure 1, the study area is district 2 of Tehran with an area of about 64 square kilometers and an estimated population of 701,303 persons according to the 2016 census of Iran. It consists of 9 urban areas and 42.2 km of first-degree arterial passages and 55.1 km of second-degree arterial passages.

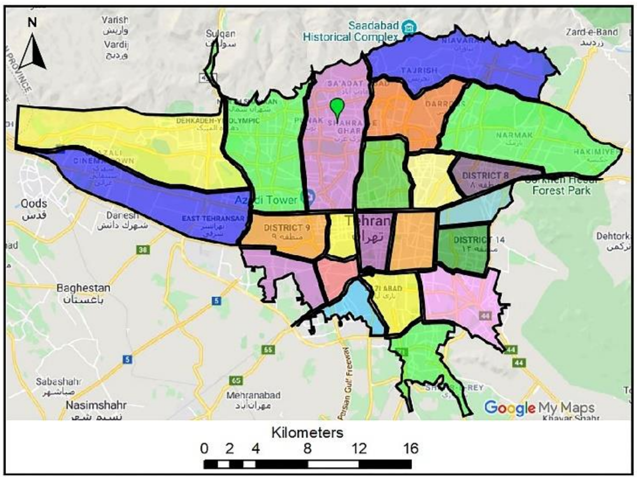

Figure 1. Districts of Tehran and location of district 2

3. The Proposed Method

In this research, after determining the extent of road damage using the vulnerability map of the buildings, an application is designed to collect crisis-related data with the help of people in crisis areas, and then the decision-making center selects blocks as priority points for relief. Finally, the process of optimal allocation of rescuers to the injured and routing in the network is done taking into account the extent of road damage (Figure 2).

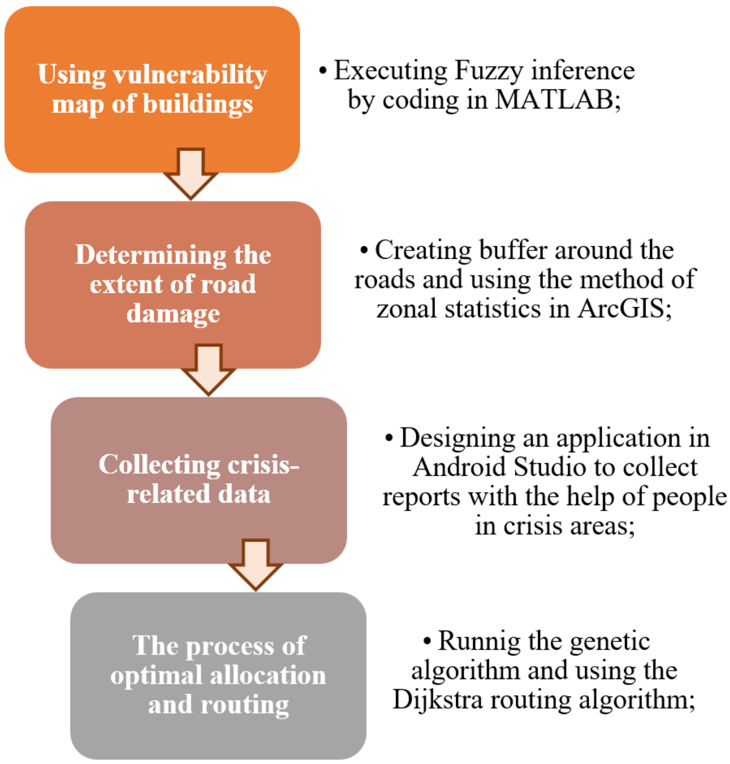

Figure 2. Proposed research method

- **Determining the extent of road damage:** The road network, as one of the components of the vital arteries of transportation, has a decisive role in the lives of people in urban areas, whose damage or destruction due to natural disasters, especially earthquakes, will cause many disruptions in urban and relief transportation. Determining the degree of damage to the arteries to plan for relief and evacuation of accident points is one of the main activities in the rescue process. The amount of destruction or opening and closing of passages in the area is affected by the amount of destruction of buildings as well as the width and type of arterial degree of passages.
- **Collecting crisis-related data:** The next step of this research is to determine the best locations in the study area for the establishment of emergency internet supplier instruments. In order to establish internet communication in times of crisis, if the existing global network is usable, such an emergency network can be easily used. In other words, a local area network can be easily and inexpensively created to cover areas tens of kilometers long. To create a local network for each area, an access point can be connected to an omnidirectional antenna and installed at the highest location. The combination of such antennas creates local coverage throughout the region. Using radio wireless devices is an appropriate and cost-effective suggestion (Frenzel, 2018). Mikrotik Wireless Radio, with a powerful antenna, will provide seamless communication. Using this instrument hand-over is done automatically and without any interruption. The antenna is a passive device and the radio is an active device. Due to their output power, radios are capable of transmitting signals to a limited extent, but adding an antenna can significantly improve both signal reception and transmission power. In other words, antennas are complementary devices to radios. Our research revealed that Mikrotik DynaDish 5 is a cheap 5 GHz device designed for outdoor use and equipped with a Gigabit Ethernet port to take full advantage of 802.11ac standard power. Theoretically, using a 5 GHz device with 802.11ac standard provides the fastest data transfer rate, at speeds of about 800 Mbps (Shin & Bagchi, 2013). This device is one of the most ideal instruments for point-to-point connections over distances up to 15 kilometers. DynaDish 5's body and cover are made from durable plastic; therefore this radio is able to make lasting connections in harsh weather conditions and is a good choice for high-frequency contamination due to the antenna cover (Chen et al., 2019).

  In this research, the effort is to provide relief more quickly and minimize human and material damage. One of the things we need in times of severe crisis is to quickly record the location and report the location of an event. Now if the location, without the need for special training, is sent in high-precision numerical coordinates by the people in the crisis areas it will have an effective contribution to the accuracy and speed of decision-making. Using VGI through mobile phones helps identify the affected areas hidden in the created vulnerability map. This simulation can be used alongside other expert systems as appropriate information and analytical tool for managing decisions regarding earthquake damage reduction.

  For this purpose, an application is written in the Android Studio environment that collects crisis reports with the help of people in disaster areas. Android is an operating system for mobile devices. A modified Linux kernel is used as Android's kernel.
- **The process of optimal allocation and routing:** We use a genetic algorithm to determine which rescuer should be assigned to which point of damage so that the total weight distance of these rescue routes is minimal. The path is selected where the least possible damage is between the relief centers and critical points in that path. Then, we use the Dijkstra routing algorithm to calculate the shortest path between two points in the network.

  The genetic algorithm is a subset of evolutionary computation involving mutation and crossover in a population of fixed-length bit strings. Genetic algorithm has been applied for several decades in many engineering problems as an optimization technique for a fixed set of parameters. First, we create a population that includes random solutions. In a binary coded genetic algorithm, model parameters representing a solution to the optimization problem are encoded by binary strings of 0's and 1's referred to as a chromosome. The algorithm starts with a population consisting of a set of chromosomes randomly selected within the search space. Then we use the roulette wheel selection method to select parents from the population and create a population of offspring. At the following, we need to write a Fitness Function which is a minimization function due to our problem. Fitness Function (also known as the Evaluation Function) evaluates how close a given solution is to the optimum solution of the desired problem. At the next step, we use crossover operators to combine the genetic information of two parents to generate new offspring. In this research, we use three different crossover operators in order to take advantages of all three methods:

  1. *One Point Crossover:* In this one-point crossover, a random crossover point is selected and the tails of its two parents are swapped to get new offspring.
  2. *Multi-Point Crossover:* Multi-point crossover is a generalization of the one-point crossover wherein

alternating segments are swapped to get new offspring.

3. *Uniform Crossover:* In a uniform crossover, we don't divide the chromosome into segments, rather we treat each gene separately. In this, we essentially flip a coin for each chromosome to decide whether or not it'll be included in the offspring. We can also bias the coin to one parent, to have more genetic material in the child from that parent.

We also need to use mutation operators. In simple terms, mutation may be defined as a small random tweak in the chromosome, to get a new solution. It is used to maintain and introduce diversity in the genetic population. The mutation is the part of the genetic algorithm which is related to the "exploration" of the search space. It has been observed that mutation is essential to the convergence of the genetic algorithm while the crossover is not. In this research, we use a bit flip mutation operator. In this bit flip mutation, we select one or more random bits and flip them. This is used for binary-encoded genetic algorithms.

Finally, we use Dijkstra's algorithm that is an algorithm for finding the shortest paths between nodes in a graph, which may represent, for example, road networks. This algorithm is also used in GPS devices to find the shortest path between the current location and the destination.

4. Experimental Results

In order to determine the vulnerability of roads in the area, it is necessary to determine the degree of damage to buildings in that area. For this purpose, a vulnerability map of the buildings in the study area was produced using Fuzzy inference by coding in MATLAB. The image of the vulnerability map of buildings is shown in Figure 3.

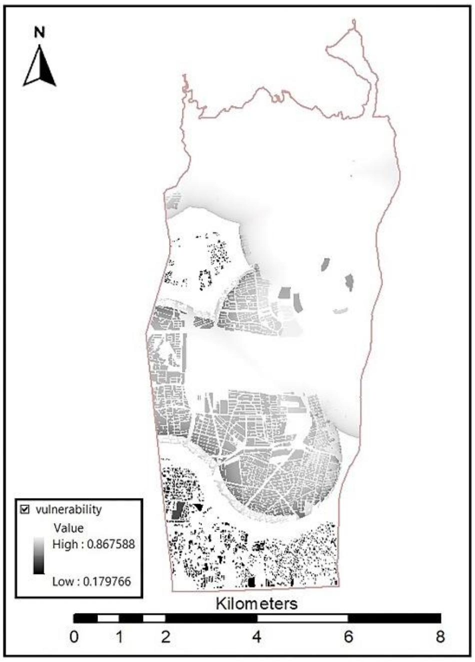

Figure 3. Vulnerability map of buildings

A 7.5-meter buffer around the roads is created and the value of the pixels that are placed inside this area is examined (this buffer shows the extent of the impact of building breakdown on the roads). The size of the buffer around the roads affected by the earthquake is determined by the height of the buildings that fall on the road due to the earthquake. With the method of zonal statistics, the average value of damage within the buffer is obtained. By converting the street vertexes to points and assigning the value of the street damage layer obtained from zonal statistics to those points, the street damage information can be attributed to the points that appear in the table of street points. With a spatial connection of street points to the linear complication of the road itself, the amount of damage is connected to the road. The amount of damage to the streets is then divided into four categories: "low", "medium", "high" and "very high". If the amount of damage is less than 1, the road is slightly damaged, between 1 to 2 moderate damage, between 2 to 3 more damage and more than 3, the most damage which means that the rubble of buildings is dumped on the road and the road is closed. In this way, it is possible to identify the roads that are open, semi-closed, and closed, and to bring the answers closer to reality, the width and type of roads can also be considered as the main work output. Therefore, the main highways and streets with a width of more than 10 meters are considered with low damage. Figure 4 shows the amount of damage to the roads after the analysis.

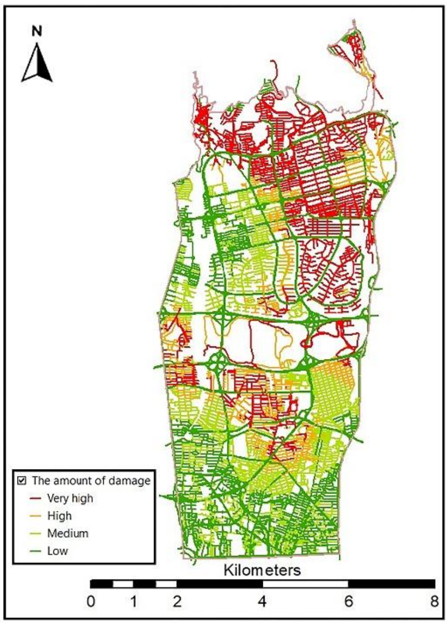

Figure 4. Amount of damage to the roads

The next step of this research is to determine the best locations in the study area for establishment emergency internet communication in times of crisis. As is mentioned, wireless radios are able to communicate within a certain range, which is considered to be circular. Due to the 15 km board of Mikrotik DynaDish 5, only two wireless radios can provide internet access in the study area in times of crisis. Therefore, the south-north extends of the area (as the largest dimension) divided into two equal parts, and the geometric center of each part was determined as the position of wireless radio (Figure 5).

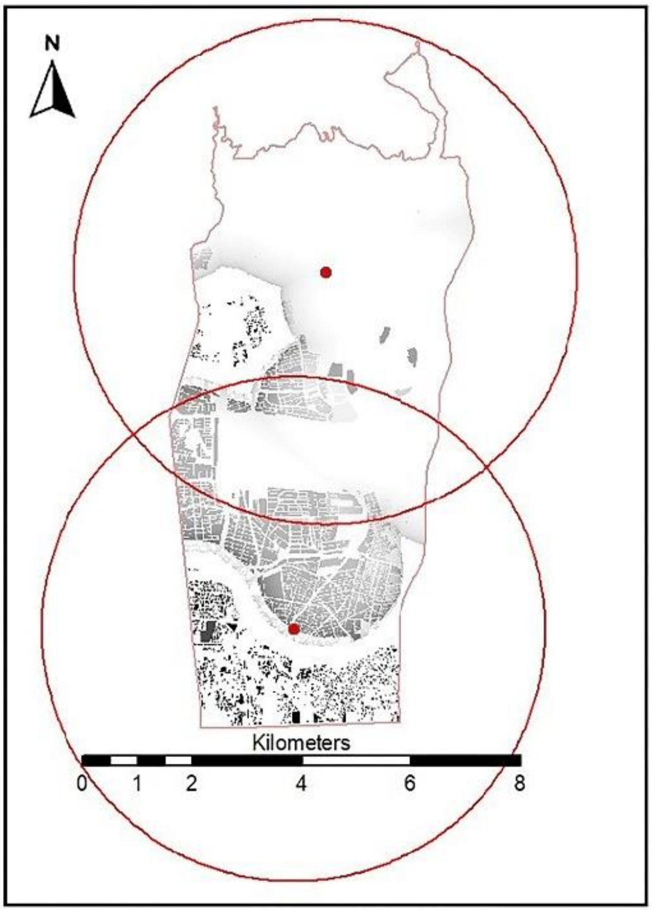

Figure 5. Position of wireless radio

After determining the best locations in the study area for the establishment of emergency internet supplier instruments, we should write an app in the Android Studio environment in order to collect crisis reports. The app is designed to allow users to easily submit reports after connecting to the internet network, even if their phone cannot be locating. In the following, the details of this app are explained. The users can register by the app before the crisis. At the time of the crisis, their location, as well as their optional message, can be sent to the relief center in the easiest way. As is shown in Figure 6, to ensure the information received first, it is necessary to register the name and mobile number.

Figure 6. Registration page

Then, the location of the person is displayed on the map if it is in a location where it is possible to locate. As is mentioned, due to the possibility of lack of location services in smartphones during the crisis, the app must be designed in such a way that the person can save locations before the crisis. So, if the locating is not available, the page of the saved places will appear to the user (Figure 7).

To save a location before the crisis, you need to select add to favorites button on the map page (Figure 8). After the user has determined the point either on the map or through the saved points, the user must determine the type of damage. As is shown in Figure 9, one has to choose an option so that the decision center can categorize the received reports and then handle them.

All user-defined specifications are stored in the user's mobile SQLite database, which is then sent to the decision center by touching the send button and confirming the reliability of the recorded report (Figure 10). Ultimately, the decision-making center collects voluntary information from affected people who use the developed app on their mobile smartphones, providing a comprehensive view of the extent of the damage in the area and can make better and faster decisions.

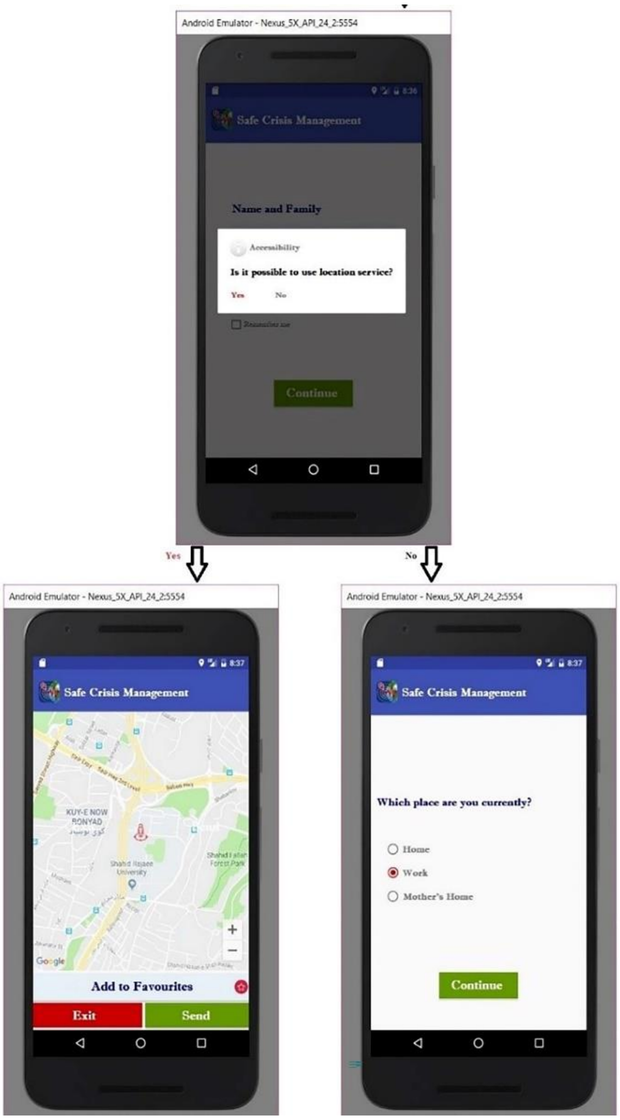

Figure 7. Location page (Using location service if possible or select saved location if not possible)

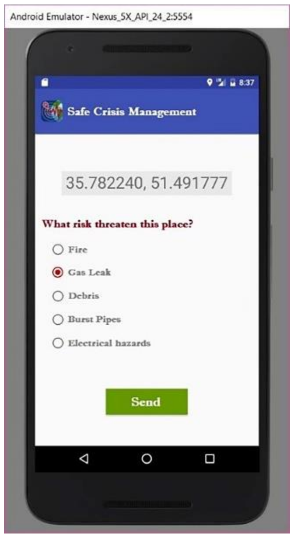

Figure 9. Determine the damage

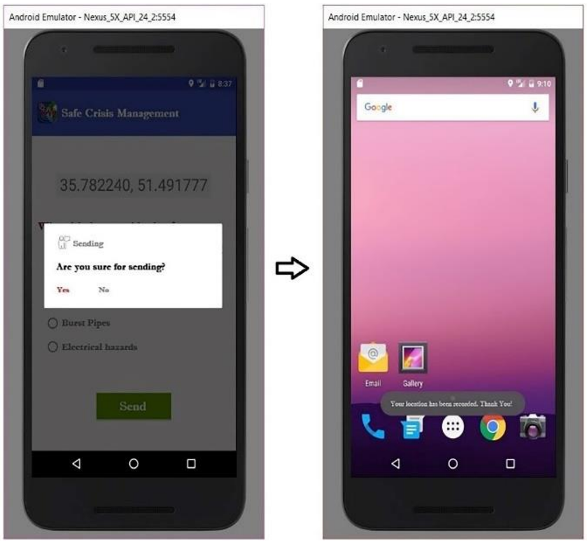

Figure 10. Verification of report

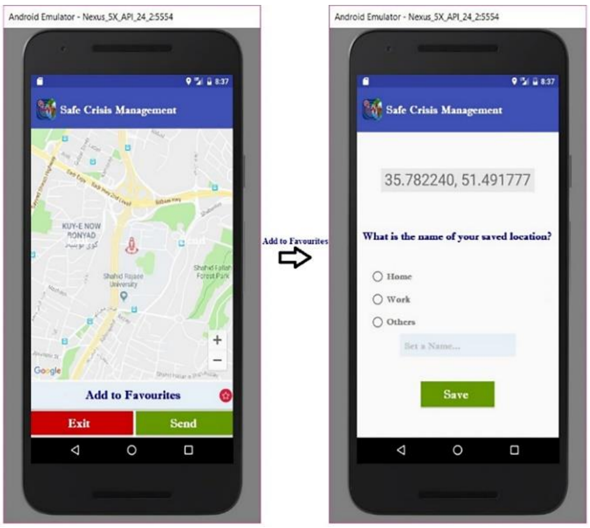

Figure 8. Save location

As is mentioned, it is assumed that after receiving public reports and classifying them by the decision-making center, considering the risk of each category, the degree of damage to the buildings in the area, and the populations of the blocks, five blocks are selected as priority points for relief (Figure 11).

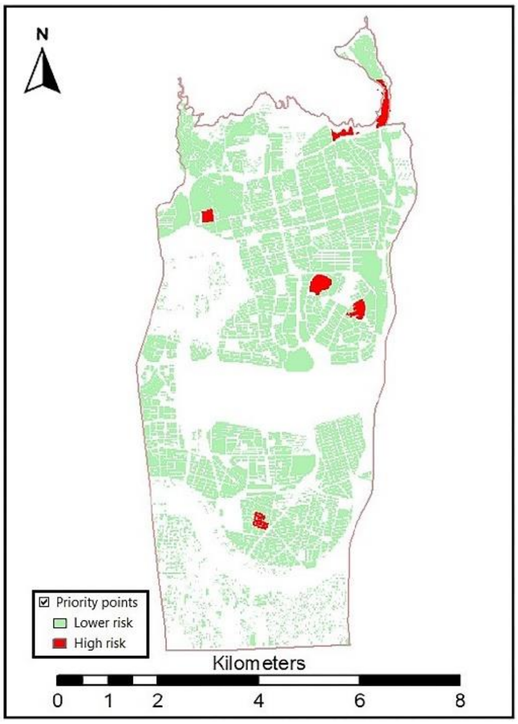

Figure 11. Priority points for relief

In order to apply the required analyzes for routing in the network and run the genetic algorithm to find the optimal allocation of rescuers to the injured, it is necessary to prepare the network. Except for GIS-ready layers, which were used in data preparation in the section of determining the extent of road damage, because our network is a weighted graph consist of nodes and edges, it is necessary to provide an adjacency or neighbor matrix of the network graph.

The adjacency matrix represents the neighborhood between the nodes of a graph. In other words, the adjacency matrix indicates whether there is an edge between the pairs of nodes. In rough graphs, this matrix shows the number of edges between pairs. The adjacency matrix element for a simple graph shows whether the edge is between two nodes. For each graph, there is a unique neighbor matrix.

As a result, this matrix is needed to find out if there is a connection between the nodes. This matrix is obtained by MATLAB programming from the existing road network. The adjacency matrix is a symmetric matrix of all network nodes whose rows and columns are the number of node points (ID points) and the values of the matrix are the weight of the connecting edge of the points or the damage obtained from the previous section. The coordinates of each network node are calculated by the number of available points in the adjacency matrix. Finally, the genetic optimization algorithm manages relief resources and allocates them to critical points. Its practical method is that a function must be introduced into the genetic algorithm in the network in such a way that it calculates the distances of the relief paths between each rescuer and each critical point. This method is briefly described below.

First, a matrix is made of relief centers and critical points. The location of the 10 relief centers in the area and the number of crisis points considered are shown on the map in Figure 12. As a result, we have a 5*10 matrix called the crisis-relief matrix, which is filled with the numbers 0 and 1. 1 means assigning rescuer number n to the injured person m and 0 means no assigning. Relief workers may be sent from one relief center to several crisis points. How to determine and assign numbers of one or rescuer to the damage is done by the optimization algorithm. The purpose of this work is to allocate the rescuer to the crisis points in the minimum distance and find the best route using the Dijkstra routing algorithm.

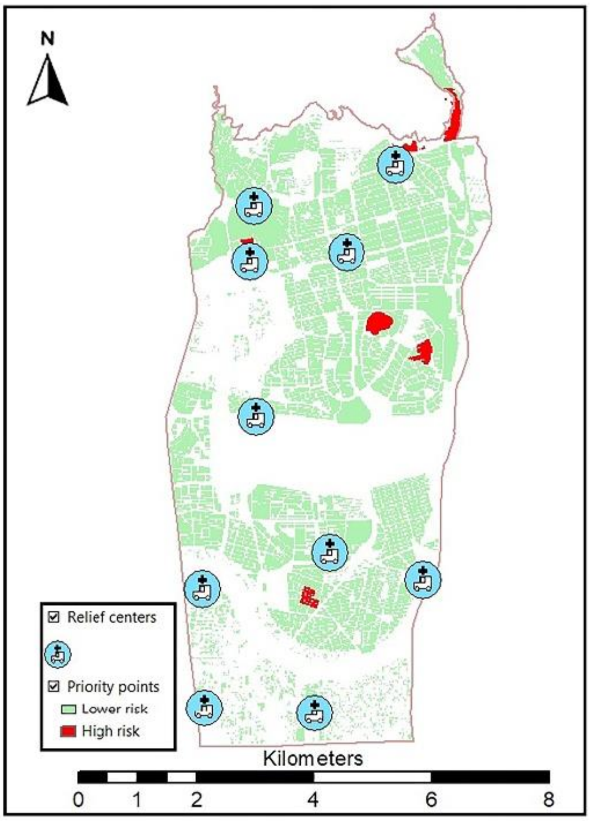

Figure 12. Relief centers and critical points

The task of the genetic algorithm is to determine which rescuer should be assigned to which point of damage so that the total weight distance of these rescue routes is minimal. This algorithm obtains the least total weight distance in the path. First, the corresponding IDs to the location of the damage and relief points (by comparing their coordinates in ArcGIS) are read from the network. The shortest route is then executed for relief and crisis points.

In order to determine from which rescuer to which critical point (Figure 13), services should be provided so that the sum of relief distances is minimized, the function f(x) must be written in such a way that in all cases, it calculates the sum of the distances of the shortest weight path between the rescuers and the critical points. Then introduce this function to the genetic algorithm to minimize the sum of distances.

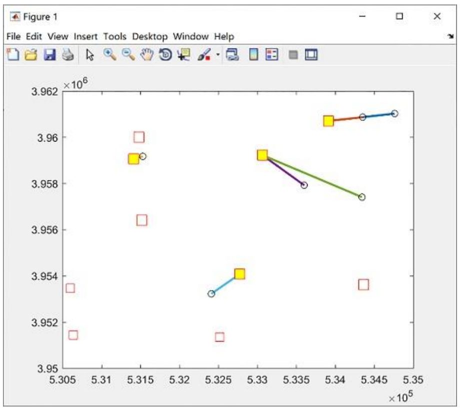

Figure 13. The graph of the results obtained for optimal allocation

Figure 14 shows how the rescuer is assigned to crisis points. The green points are the relief points and the red points are the crisis points. Relief 1 goes to Crisis 1, Relief 4 goes to Crisis 2, Relief 2 goes to Crisis 3, Relief 2 goes to Crisis 4, and Relief 6 goes to Crisis 5, in which the sum of the weighted relief-crisis distances is minimal.

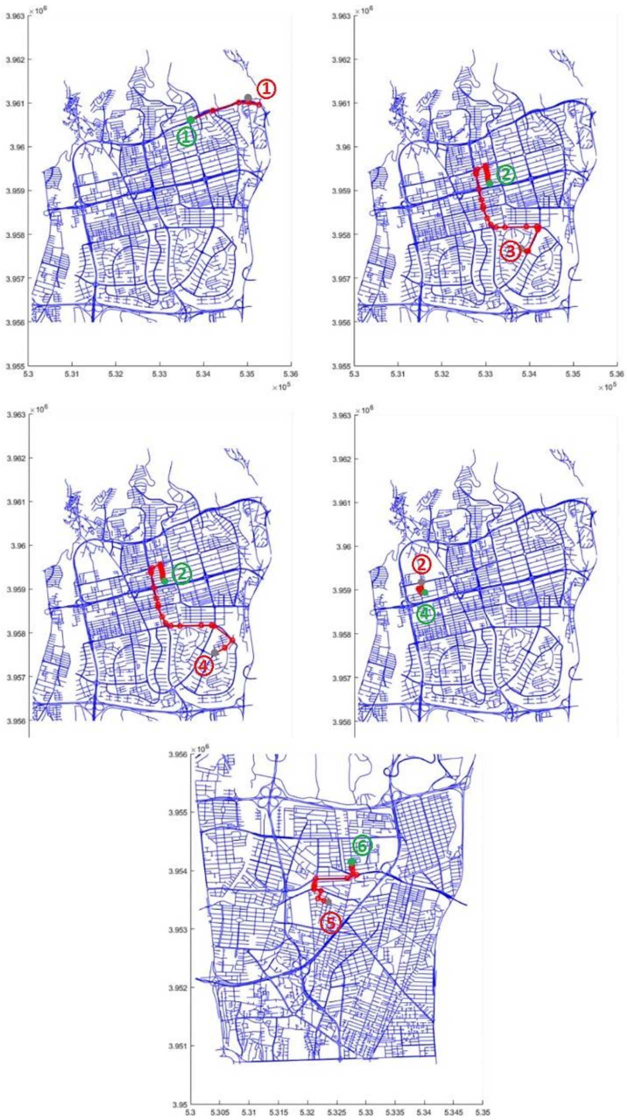

Figure 14. The shortest route between relief and crisis points

5. Discussion

Since most of the required information related to crisis management and urban planning activities is spatial information, in this regard, the science and technology of spatial information systems are used to help make appropriate decisions in crisis management. But this system does not always meet all the needs to solve a problem. In this research, in addition to the spatial information system, one of the branches of artificial intelligence has been used to simulate the critical environment and by combining these two systems, we have reached more appropriate analyzes related to earthquake crisis management.

One of the necessary activities after a crisis such as an earthquake is to provide rescue services to the public as soon as possible. Meanwhile, the allocation of relief forces to the victims and the routing of these forces is one of the first problems faced by rescue teams. In the present study, finding the most appropriate relief allocation for relief groups by considering the most appropriate and shortest route in terms of the amount of damage by the intelligent allocation factor or optimization algorithm in critical post-earthquake conditions has been considered. In choosing the most appropriate route for rescuers, the simulation conditions should be as close as possible to the actual conditions of the post-earthquake area so that the results can provide efficient information to crisis management decision-makers.

Simulation and intelligent allocation make it possible to become somewhat familiar with the issues and problems that arise before an event such as an earthquake occurs. Then, in order to solve it in the form of a simulated environment, it carried out relief activities according to different conditions and the importance of time in it. In the present study, the MATLAB programming language has been used to develop these characteristics and apply the genetic optimization algorithm. In order to know the amount of damage to buildings and as a result of passages, fuzzy inference method and MATLAB programming have been used. The navigation environment is modeled as a graph in which nodes, network decision points, and edges simulate lines of motion. The rescuer assignment function to the sighted points directs the rescue force based on the shortest weight distance between the origin and the destination according to the genetic algorithm. Successful routing is by scrolling from the start node to the end node. Dijkstra routing algorithm has been evaluated in this process and has been considered in the rescue process. Finally, by collecting accurate voluntary information from people in the affected areas, a more comprehensive view of the extent of damage in the area is obtained, which identifies the hidden points and significantly reduces the damage. This simulation can be used alongside other expert systems as a piece of appropriate information and analytical tool for management decisions related to earthquake damage reduction.

In recent years, the use of artificial intelligence concepts and especially the modeling approach to solve problems related to crisis management has been considered by most researchers and scholars. Most of the new models developed in this field have advantages over the previous models. In fact, the purpose of creating new models is to improve the weaknesses of previous models and thus improve the results. In this regard, the model developed in this study also has advantages over previous models in this field.

The use of the genetic algorithm as a factor in allocating relief resources to crisis points in the most optimal case and also the use of this algorithm in routing rescuers is one of the capabilities of the developed model. Using this algorithm, the most suitable route in terms of the least damaged passages is selected to send relief forces to the destination. The use of Dijkstra routing algorithm within the algorithm allocation model and the use of weight (damage) of all possible paths from the decision point to the destination to decide on the optimal paths are also among the innovation points of this research.

Finally, the most important innovation used in this study is to provide a solution to provide Internet in the affected area and use the participation of people in the discussion of identifying the affected areas by sending the exact coordinates of these points using mobile phones.

6. Results

The main result of this study is the implementation of a simulation environment for the allocation of relief and routing in the post-earthquake environment. This simulation is based on routing in an earthquake-stricken city. Since, choosing the most appropriate way to reach the injured will have a great impact on the relief process, in the simulation, an attempt was made to bring the data used close to the existing conditions in the region after the earthquake.

On the other hand, people's voluntary reports are used to gain a better understanding of the situation after the crisis and identify hidden areas. For this purpose, it was necessary to provide internet in the area and program a practical app for people. Based on this research also the following consequences were achieved:

- Volunteer peoples' data collected with mobile GIS, helps us to observe the hidden dangers in the region and reduce the amount of damage by responding quickly.
- Based on the arterial vulnerability map created, planners and city managers are able to review previous urban planning strategies and develop new ones.
- With this model, it is possible to estimate the number of necessary reserves required in times of crisis, which helps to respond quickly to the needs of victims in times of crisis. Especially if we consider that the existing budget and efforts for seismic events are often limited or even inaccessible.

Generally, this model can be suitable and efficient for use in hazard mitigation as well as estimation of required resources in the disaster management cycle.

7. Conclusions and Recommendations

This paper showed that GIS-based analyses are a useful approach for earthquake disaster management—before, during, and after the occurrence of an earthquake. Providing people with a user-friendly application for asking for help or reporting the situations can play a critical role in the crisis management process. After finding the high-risk points, it is necessary to determine the shortest and least damaging route to the points. For this purpose, the amount of road damage should be calculated and then the best route should be determined through optimization algorithms.

Considering that the crisis simulation method is a relatively new topic in the field of crisis management, in this field, less applied research has been done in the country and less attention has been paid to it. On the other hand, difficult access to real crisis management data to validate the research was one of the difficulties of the research. Besides, for programming in MATLAB software, in order to estimate road damage as well as allocation by genetic algorithm method, raster data is required, unfortunately, data accuracy is reduced in converting vector data, which is the original format of primary data, to raster data and raster analysis.

Using Mobile GIS in this study allowed the exploitation of the data collected in every situation and fill the gap between the people, the crisis headquarters, and the relief teams in order to diagnose the most vulnerable zones. A spatial analysis made it possible to locate the structures and the extent of damage from the blocks of buildings on the adjacent roads. Through this study, now we know the vulnerable roads in the study area help headquarters and relief decisions to be faster and better.

The results clearly demonstrate the high vulnerability of the region and the fragility of its urban texture. As is mentioned, about 243.5 km of the region's roads are damaged by at least 80% that makes the relief process difficult. These research results may be useful in the organization of the first aids, reinforcement of buildings, and reconstruction's actions. However, using people's smartphones as data collection tools in crisis management processes such as earthquake disaster basically requires high tech geo-informatics infrastructures such as comprehensive geodatabases at fine resolution, equipped with strong hardware and rapid software.

In this study, in order to evaluate the allocation and routing process, complexities such as the traffic situation in the urban environment at the time of the crisis have been omitted and only a summary model of the study area has been prepared. Therefore, to develop this research, it is recommended that the real simulation of the environment be done by considering different dimensions of urban complexities.

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