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Strategy for Effective Evacuation of Pedestrians Using GIS and GPS Measurements

Nikos Polakis, Androniki Tsouchlaraki

School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece
Email: nikospolakis@gmail.com, niki.tsouchlaraki@enveng.tuc.gr

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Abstract

During a residential settlement evacuation, a large number of individuals do not have access to any private means of transport in order to be evacuated; these people are assembled at Evacuation Assembly Points (E.A.P.s), so as to be picked up, gathered and evacuated by the competent authorities. The present study aims to evaluate whether some pedestrian assembly points are adequate for these people's fastest assembly, taking into account the demographic characteristics of the studied population and the incline of the studied area's ground. In order for said fastest assembly and evacuation to be achieved Geographical Information Systems (G.I.S.) and GPS measurements have been employed. The suggested method has led to the creation of the households' classification maps based upon their inhabitants' response time in order to improve the pre-existent Intervention Teams' contingency plans. First, in order to identify the demographic characteristics of the studied population, we have employed the field survey method; second, we have determined the fastest and ergo optimal evacuation routes using the Dijkstra algorithm. What is more, the results hereof prove that it is feasible that the time it takes to gather the pedestrians be optimized by way of choosing the best evacuation point, whilst a method of large crowds' evacuation in groups has been developed. The latter could constitute a useful tool for Civil Protection Agents and responders.

Keywords

GIS, Evacuation, Control Strategies, Disaster Response, Fire Safety

1. Introduction

The simulation of the evacuation of a specific area could constitute a useful and determining factor for the decisions that shall be taken by the Authorities when a group of people is threatened by a natural disaster. Kim Tae, H. *et al.* [1] have pinpointed the need for the development of tools to inform, prepare and train the government-appointed agents, administrators and responders to make decisions in case an emergency arises. Any lack of proper and adequate planning might result in delaying the evacuation and by the same token human lives might be in danger. For the aforementioned reason, Dapeng Li, Thomas J. Cova, Philip E. Dennison [2] have used the simulation of the aforesaid hypothetical scenario for the development of an evacuation decision-making procedure. Using spatial analysis methods and employing Geographical Information Systems (GIS) they have developed a method to delimit wildfire evacuation trigger points, whereby an order to evacuate is given when a prominent wildfire crosses a specific point. The decision to evacuate an area having been made not with standing, residents shall also know where to go, how to safely evacuate the area and which route to follow [3]. The manual developed by the U.S. Department of Transportation [4], in order to guide Crises Administrators in aid of populations with special needs, makes allusion to several reasons (indicatively: financial ones, health issues, environmental awareness, lack of driver's license), for which some of the inhabitants are deemed "transportation disadvantaged"; this is due to the fact that they do not own or possess any means of transport that could be utilized for their evacuation. These people shall abandon the dangerous area to reach a safer point on foot. This process is mentioned as "pedestrian evacuation" [5].

Earlier studies analyzing pedestrian mobility models during a natural disaster have shown that there can be an estimate of the time needed by the mean person to reach a safe point using GIS [6] [7].

In order to improve the evacuation procedure, it is of essence that the evacuation time decrease. The study by Lakshay Taneja, Nomesh Bolia (2018) [8] applied upon a hypothetical network indicated that guidance significantly decreases the evacuation time—in comparison to a spontaneous evacuation; the latter is defined as an evacuation without any prior planning or guidance. One among the plausible interventions/approaches to decrease the evacuation time is to provide the evacuees with information about the evacuation routes, estimated time of travel and their EAP (Evacuation Assembly Point).

We have conducted a study with the intent to develop a strategy to evacuate the pedestrian inhabitants of a residential settlement threatened by a prominent forest wildfire; in order for this to be achieved, we have used GIS and GPS topographical measurements. Our focus has been on the following questions:

A. Can the evacuation time of a residential settlement improve or does it remain the same in every scenario?

B. How are the demographical characteristics of the population, the geographical position of each surveyee's residence and their response time during the evacuation correlated?

C. Can the pedestrian inhabitants of an area be gradually evacuated for their own safety?

The results have shown that a fair estimate of the pedestrians' evacuation time [Tievac] is possible, taking into consideration the populations' characteristics, as well as the area's topographical features (altitudes, landforms, distances and evacuation routes' elevations). In parallel, the time it takes to assemble the pedestrians can decrease by way of choosing the optimal EAP. In conclusion, we have developed an evacuation method for the population, which depends upon their gradual arrival at their respective pedestrian EAPs.

Our study has resulted in the development of a concise methodology that decreases the assembly time of the pedestrians. The key tool we have employed is to find the optimal assembly point; in parallel, our study introduces the concept of "evacuation groups" or "evacuation in groups" (see infra Chapter 4.3). For the development of this new concept, the pedestrian evacuees needed to arrive at their assigned EAPs gradually in order to avoid dangerous and unnecessary crowding.

To paraphrase all the aforementioned, previous studies have been focusing on the evacuation time, but have not shed light on how to minimize it; another contribution to the pre-existent bibliography is the choice of the optimal departure point for each pedestrian and subsequently the determination of the optimal EAP for them. The last two elements have neither been discussed or researched into in previous studies.

2. The Study Area

The area of study (**Figure 1**) has been a residential settlement in Crete, Greece, located 18 kilometers from the city of Réthymnon at an altitude of 350 meters. The acreage of the residential settlement's cohesive part is approximately 50.000 m2 and it has a population of 105 residents. Its cohesive part comprises narrow lanes that lead to the yards and main entrances of the residences with steep fluctuations in elevation points (0% up to 13%).

This particular residential settlement has been chosen for the characteristics enumerated below. First, its population is not dense, which goes a long way for an evacuation study. Second, it is surrounded by a high vegetation cover; the latter in conjuction with the area's steep incline renders the settlement forest wildfire-prone. Last but not least, the vast majority of its population (67%) is transportation disadvantaged (**Figure 2**), which in turn means that in case of an evacuation they must be picked up by the competent Civil Protection Teams.

This percentage is so high, due to the fact that the vast majority of the population in question consists of elderly people (54% among them are over 55 y.o.). The high percentage in transportation disadvantaged senior citizens is due to financial factors and the fact that they have reached the upper age limit for driving a car. What is more, most of the inhabitants do not own any vehicle, either because their need for transportation outside their settlement is minimal to none, or because they would rather avail themselves of public means of transport.

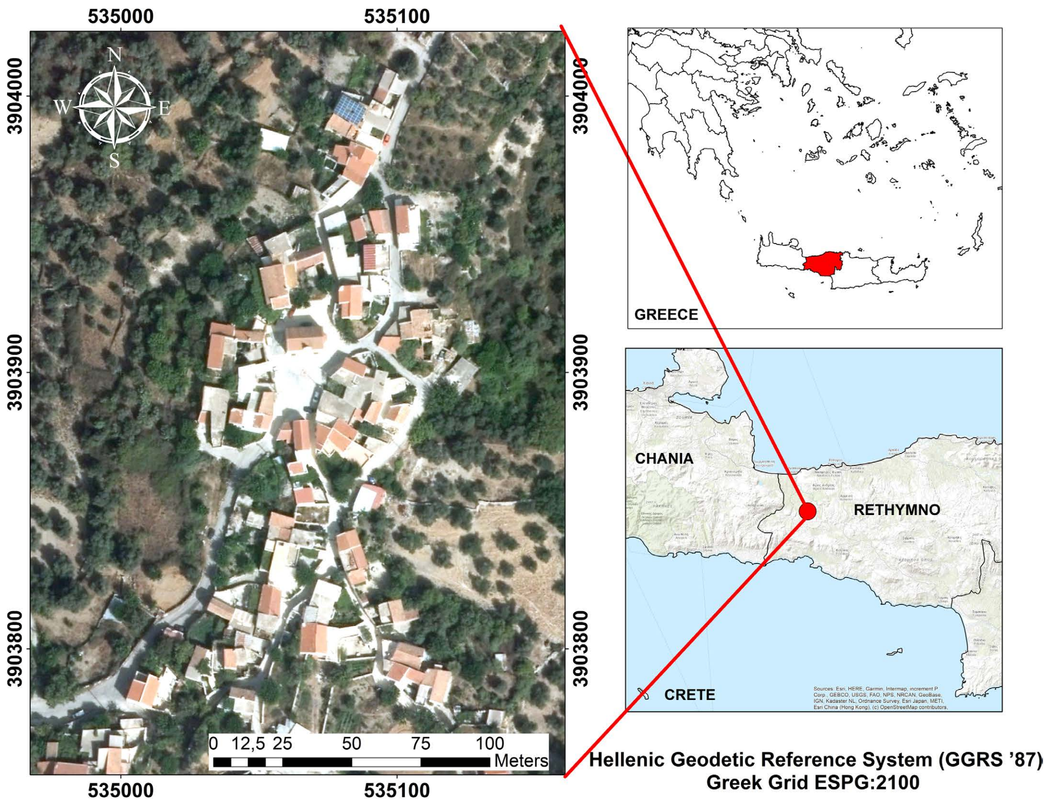

Figure 1. Study area (source: National Greek Cadastral).

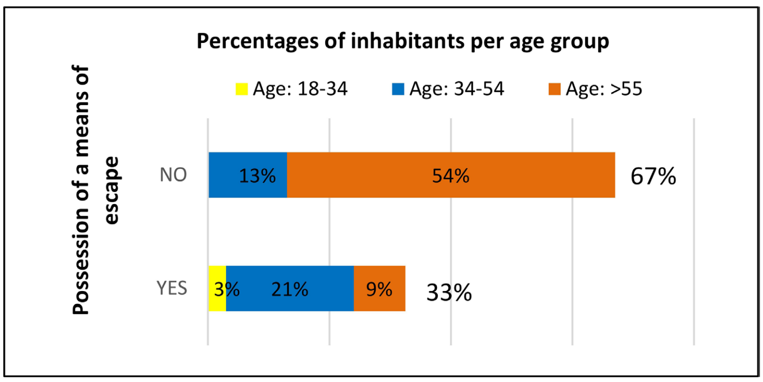

Figure 2. Percentages of inhabitants per age group in conjunction with whether they own or possess a means of escape

3. Data and Methodology

3.1. Data Collection

For the purposes of the present study, at its outset, data relevant to the residential settlement were collected, orthophotomaps from the Greek Land Registry's Archives, images and information about inhabitable residences, to name but a few. Furthermore, surveys were utilized in order for a correlation among the position of each residence on the map, the number of people living therein, their sex and whether or not they own or possess a private means of transport to be established (Figure 3). The residents/surveyees were asked which part of their settlement they would choose to approach in case of an evacuation and how much time it would take them to evacuate their house. The completion of the surveys took approximatively 1.5 months, whilst the major hindrance we encountered was to find which among the residents are permanent or temporary ones (several surveyees were indisposed or absent when we visited their residences) and therefore create an entry for the latter in our study.

1. SEX
a. Male b. Female
2. AGE
…………………………………………………………………………....................
3. VEHICLE
a. Yes b. No
4. WHICH PLACE WOULD YOU CHOOSE TO APPROACH IN CASE OF EMERGENCY?
………………………………………………………………………………………..
5. HOW MUCH TIME OF PREPARATION WOULD YOU NEED IN CASE OF EMEGERCY?
………………………………………………………………………………………..

Figure 3. Survey.

3.2. Incline Analysis and Emergency Routing

In the next phase, every possible route of the settlement was mapped utilizing the ground-based topographic mapping method. The data were collected at field utilizing the Real Time Kinematic (RTK GPS) surveying system (**Figure 4**). The

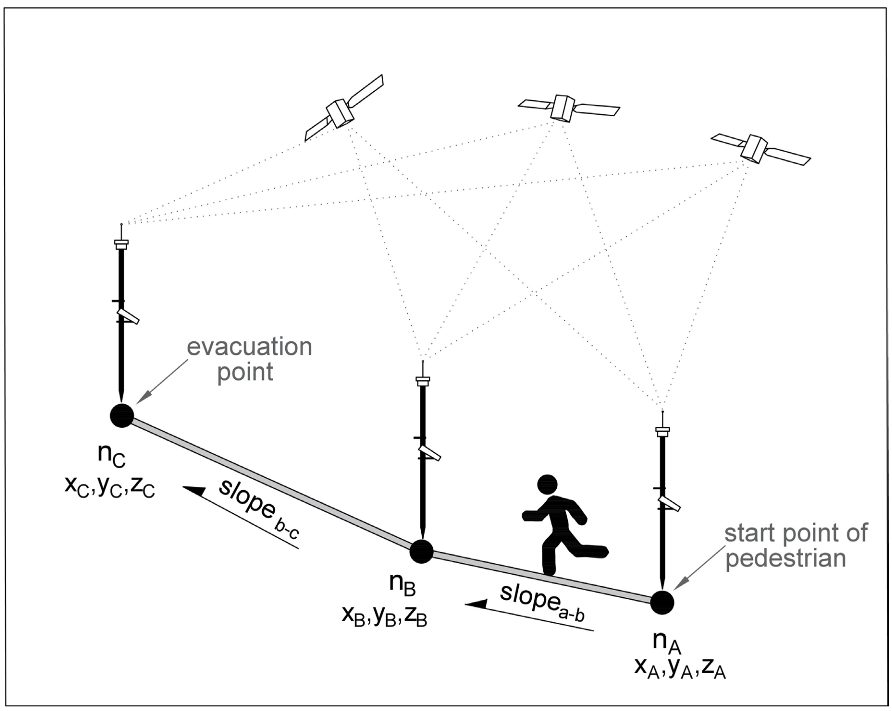

Figure 4. Evacuation routes measurements with GPS.

mapping procedure's purpose was to determine the incline of escape routes and the distances between them. The next step was to insert the collected mapping data into an ArcGIS software program in order for the escape routes to be planimetrically and altitudinally modeled.

At this point it shall be borne in mind that a pedestrian's speed is highly important for their movement's parameterization. The study by K. Aghabayk *et al.* [9] analyzing the impact of the ground's incline in conjunction with the pedestrians' physical traits on their speed has shown that each and every age group develops different walking speeds on different surfaces. Moreover, the older the pedestrian, the slower they can jog; this is a significant decrease in speed, which shall also be borne in mind in case of an emergency. For the purposes of the present study, we have set the jogging speeds as illustrated on **Figure 5** as the typical evacuation speeds.

Type of movement: Walking

Age	Type of slopes: Steep Downhill	Gentle downhill	Level	Gentle uphill	Steep uphill
Young	1.55	1.46	1.45	1.45	1.38
Middle	1.5	1.45	1.42	1.35	1.28
Elder	1.22	1.18	1.19	1.22	1.14

Type of movement : Jogging

Age	Type of slopes: Steep Downhill	Gentle downhill	Level	Gentle uphill	Steep uphill
Young	3.28	3.54	3.33	3.26	3.06
Middle	2.49	2.7	2.54	2.49	2.31
Elder	2.3	2.37	2.32	2.19	2.08

Note: Speed measurements are in m/s.
Slope: level (0%), gentle downhill and uphill (±6%), and steep downhill and uphill (±12)

Figure 5. (Aghabayk, Parishad, Shiwakoti, 2020) [9].

The prevailing condition we have set for the purposes of the simulation has been an evacuation taking place at daytime, where the lighting is deemed adequate; under this condition, the pedestrians' movement towards their EAPs is unhindered. In a future study, it would be useful to know whether the pedestrians' speed would decrease at night time, when the lighting is dim and ergo inadequate, in advance.

Similarly, for the purposes of our study, we have taken it as a given that the immediate evacuation signal [Tw] was sent to all residents simultaneously by text message on their cell phones, whilst the Civil Protection's responders, who were already in their vehicles at the EAP were transmitting voice clips with instructions to the population during the entire evacuation procedure.

The total time it takes a pedestrian to be evacuated Ti_{evac} in every scenario comprises two addends; the pedestrian's time of movement [Ti_{mov}] and the time it takes them to prepare for the evacuation [Ti_{prep}] (**Figure 6**).

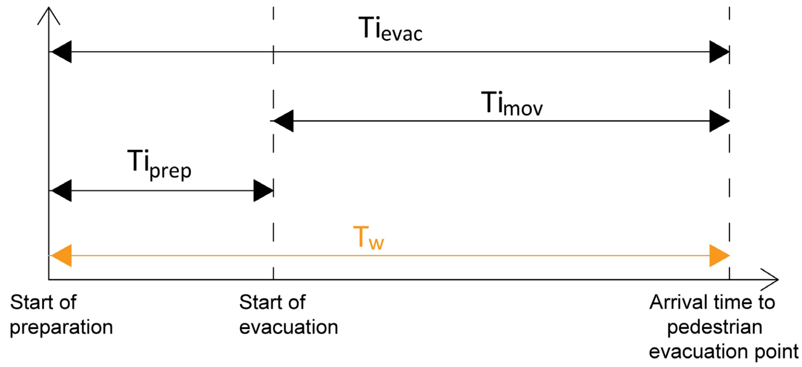

Figure 6. Schematic of pedestrian evacuation timeline.

$$Ti_{evacA} = Ti_{prep} + Ti_{movA}$$
$$Ti_{evacB} = Ti_{prep} + Ti_{movB}$$

($i = 1, 2, 3, \ldots, n$)

where n = total pedestrian population.

Ti_{prep}: the preparation time is the same in both scenaria; this conclusion was reached after the interpretation of the data collected and the analysis of the results from the survey. The key factor that determined the Ti_{prep} was each surveyee's estimate of the time it would take them to pack a "go bag" ready with some critical items, if advised to evacuate. Nonetheless, the evacuees' reaction when in panic is deemed a determinant for the Ti_{prep}. The panic factor could be the object of a future study.

Ti_{mov}: each pedestrian evacuee's time of movement is determined by the distance they have to cover and their speed towards the evacuation point.

$$Ti_{movA} = Di_A / Ui_A$$
$$Ti_{movB} = Di_B / Ui_B$$

Di: Distance between the evacuee's residence and the evacuation point.

Ui: The evacuees' speed was set based upon the study by K. Aghabayk *et al.* Aghabayk *et al.* (2020) (**Figure 5**) that used the inclines of the distances to be covered as the primary parameter. Each unique Di's incline resulted from topographical GPS measurements (**Figure 4**).

3.3. The Dijkstra Algorithm

The Dijkstra algorithm [10], (a single source shortest path algorithm) has resolved the problem of finding the shortest path between two nodes (*i.e.* the evacuee's residence and the EAP) in a directed graph with non-negative edge weights. Its use is a prerequisite for finding the shortest path to be followed by a pedestrian in their settlement in order to reach the EAP. In this algorithm, a common variant fixes a single node as the "source" node and finds the shortest path from any node to the destination node (the EAP) (**Figure 7**). Among all "unvisited" nodes, the one with the lowest weight is selected as the next one. In the present study, the shortest path is the one that corresponds to the smallest tentative distance (low weight equals short length).

DISTANCE	SHORTEST PATH
Min.	Selected
Max.	Not Selected.

Figure 7. Impact of distance on path [11].

The algorithmic process is completed when all the nodes are completed [11]. By way of illustration, on Figure 8, the paths selected are from A to B and thereafter from E to F and the shortest one is indicated in green (A-B-E-F).

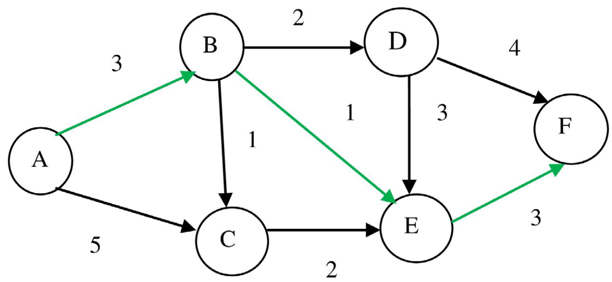

Figure 8. Example for the shortest path (Singal and Chhillar, 2014). [11]

3.4. Network Analysis

The ArcGIS network Analysis software can be used to find the shortest path in city networks and residential settlements; it can also be used to calculate the optimal paths from various points within the network towards a single point utilizing the Dijkstra algorithm. The three-dimensional network model that develops consists of nodes and lines; the first represent the residents' houses and the latter the communication pathways between two nodes, in order for the pedestrian evacuees to be able to move from one endpoint to another, with the EAP being the destination node (Figure 9).

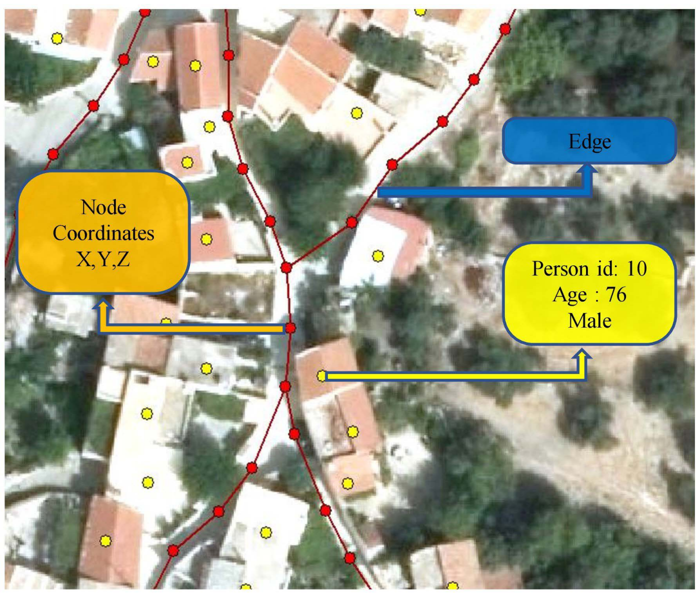

Figure 9. Modeling of pedestrian evacuation path network in ArcGis.

3.5. Emergency Evacuation Scenarios

Two scenarios based upon the two prevalent EAPs that came up from the surveyees' answers have been simulated on this picture. In particular, 68% of the surveyees answered that they would choose the square of their settlement as the evacuation point (point A), whilst 26% among them opted for the school (point B) and the remaining 6% indicated other points. The starting point for each pedestrian is their residence and for each and every one of them two possible routes developed, one for each evacuation scenario (Figure 10).

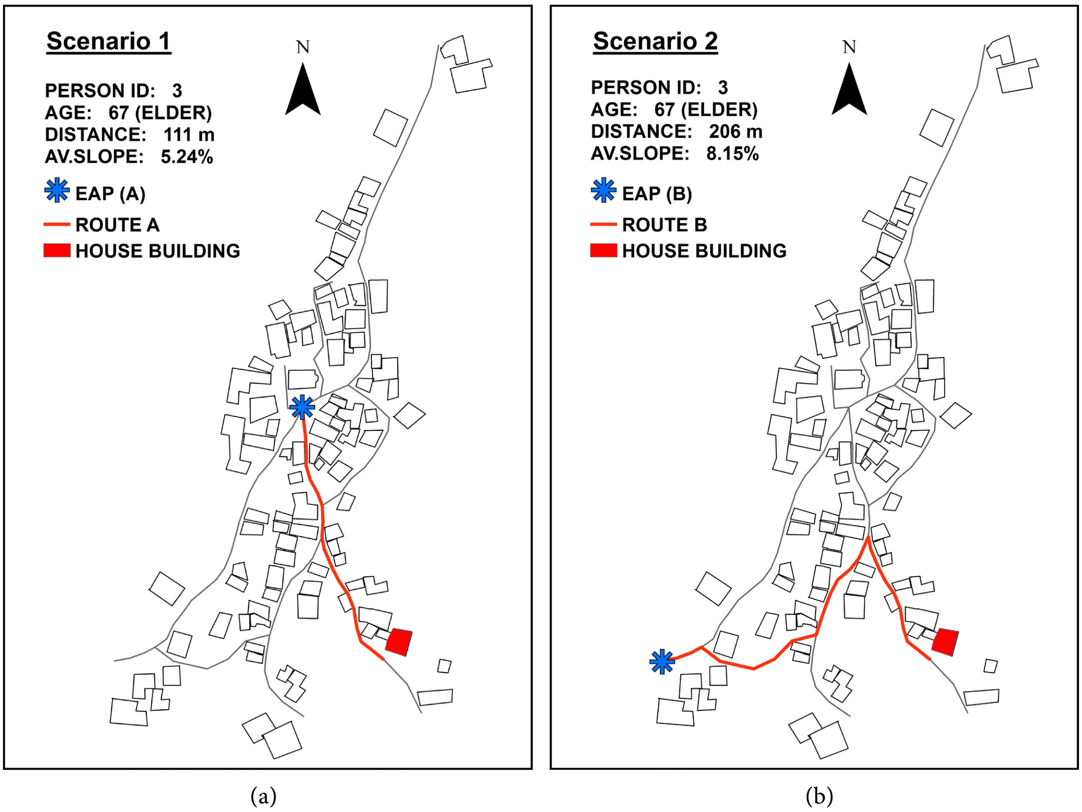

Figure 10. Example of pedestrian shortest path in each Scenario.

4. Results

In this chapter the results of the two scenarios applied to find the two most suitable evacuation points in the settlement in question are to be further analyzed. Through this procedure, the study has attempted to predict the choice of the best evacuation point by way of thoroughly comparing the evacuation time [Ti_{evac}] for each individual.

The results have been categorized into three classes and thereby risk maps utilizing the gradation of colors method have developed. Chiefly, the purpose of such a map is to be clearly and easily read by people who do not have any prior experience either with GIS or with how to deal with emergencies. Each resident is categorized into one of the three classes on Figure 12 based upon the time it would take them to reach the evacuation point from their residence [Ti_{evac}]. For residences inhabited by one or more people, the individual with the longest evacuation time is the determinant for the gradation of colors.

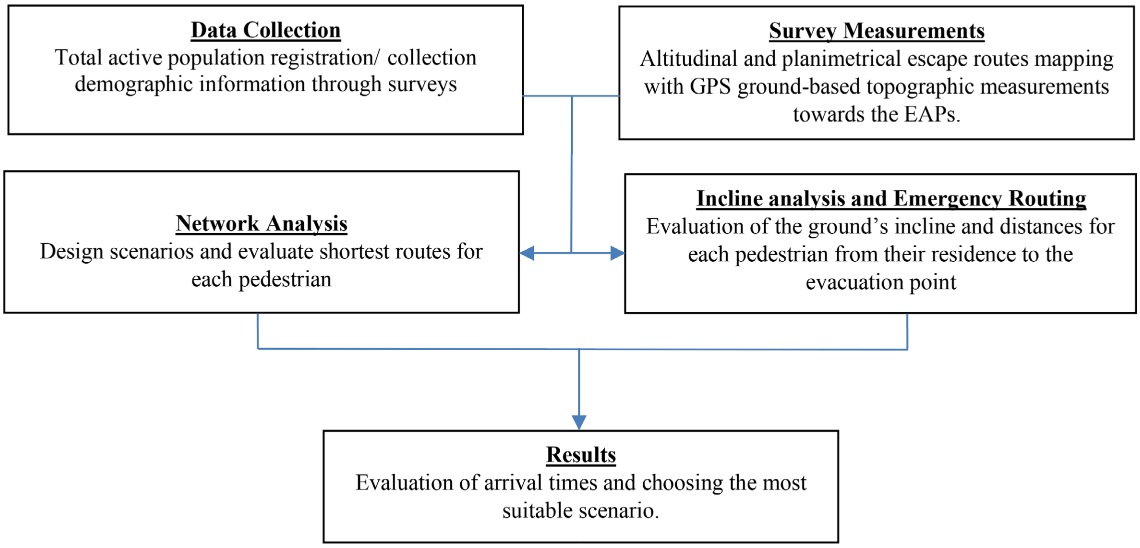

Figure 11. The flowchart of the proposed method.

	CLASSIFICATION			
Type:	A	B	C	D
Evacuation time[Ti_{evac}]:	less than 16 minutes-time.	less than 25 minutes-time.	more than 25 minutes-time.	Outside the scope of this study

Figure 12. Table of evacuation time classification.

- **Type A**: The pedestrians' evacuation time is deemed especially adequate.
- **Type B**: The pedestrians' evacuation time is deemed adequate.
- **Type C**: The pedestrians' evacuation time is longer and the Civil Protection Teams/responders shall focus on this category of residents.
- **Type D**: The residents own or possess a means of escape (thereby they do not fall under the category of "pedestrians")/Outside the scope of this study.

The procedure (Figure 11) allows the user to know the evacuation time [Ti_{evac}] for each individual residing in the settlement in question, as well as the escape route that is to be followed by the pedestrian through a single model mapping system for escape routes in advance.

4.1. Scenario 1

In the first scenario, the EAP was the settlement's church. The church is located in the central square. The church is deemed as a suitable EAP, because should the evacuees assemble at this point, their waiting time until the Civil Protection's vehicles arrive to pick them up is minimal. The church's altitudinal difference in comparison to the largest part of the settlement is relatively small, and thus the travelling distances are minimized and the residents' speed respectively increases.

The simulation has shown that less than 39% of the residents would be able to evacuate the settlement in less than 16 minutes-time, 35% of them would be able to evacuate in between 16 minutes-time and 25 minutes-time and last, 26% in more than 25 minutes-time. In this scenario, we have observed that an increased percentage of the residents are categorized under type A; this is due to the fact that the distances they need to cover have been equalized, as the church is located- from a spatial standpoint—in the center of the residential settlement. The results of scenario 1 are illustrated on Figure 13.

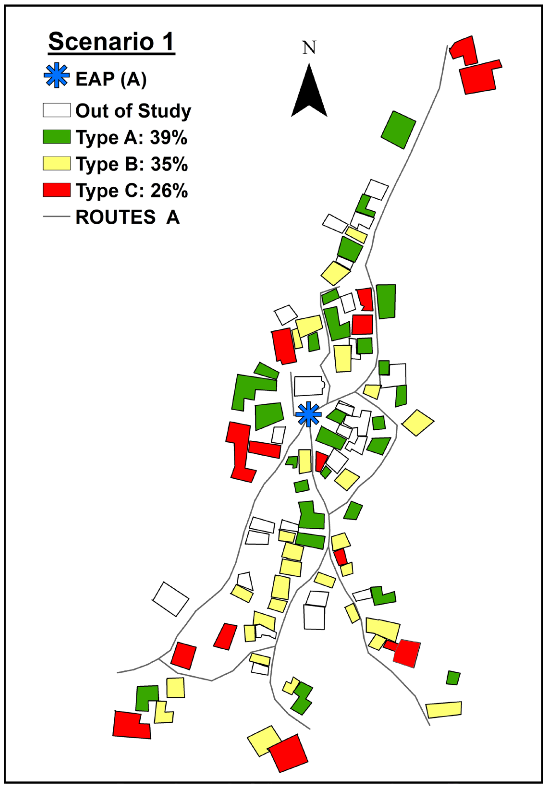

Figure 13. Scenario 1 results.

4.2. Scenario 2

In the second scenario, the EAP was the settlement's school. The school is located in the settlement's south exit; a point through which the main road leading to the nearest residential settlements passes. The school has a courtyard, from where the Civil Protection's vehicles can safely depart.

The simulation has shown that than 29% of the residents would be able to evacuate the settlement in less than 16 minutes-time, 51% of the residents would be able to evacuate the settlement in between 16 and 25 minutes-time, whilst 20% of the residents would be able to evacuate the settlement in more than 25 minutes-time. In this scenario it is crystal clear that the number of residents categorized under type A significantly decreases. This is chiefly due to the fact that more pedestrians had to cover longer distances with a steeper incline in comparison to scenario 1. Nonetheless, the slight decrease in the type C percentage is due to the shorter distance between the evacuation point and the residences located in the settlement's southern part. The results of scenario 2 are illustrated on Figure 14.

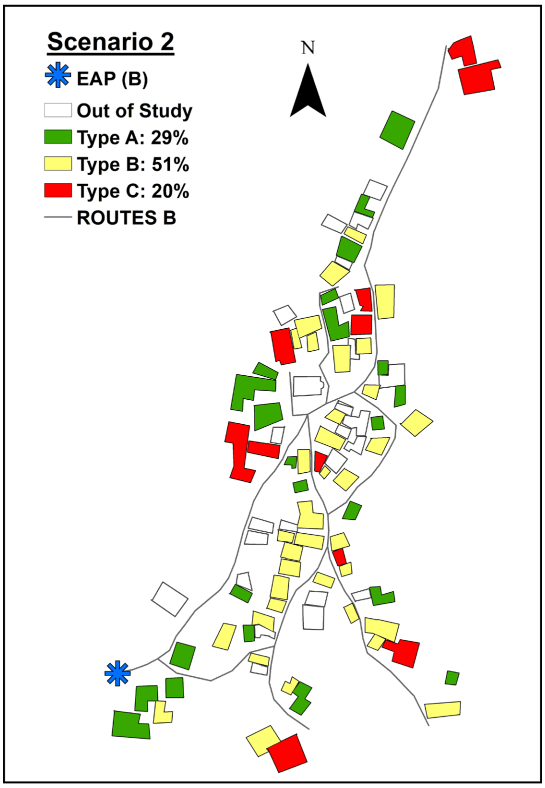

Figure 14. Scenario 2 results.

4.3. Choose the Optimal EAP (Evacuation Assembly Point)

The choice of the optimal EAP is crucial in order to minimize the time it takes to assemble all pedestrian evacuees.

The surveyees aged between 35 - 54 needed approximatively 16 mins of preparation time on average, the surveyees over 54 years of age needed 22 mins on average, whilst the youngest surveyees aged between 18 and 34 ετών needed approximatively 12 mins of preparation time. In both scenaria, the preparation time remained the same for all pedestrians, whereas the difference in the assembly time came up from the different distance and incline the population needed to cover so as to reach their EAP.

A function of the percentages of the evacuees who arrived at their EAP and the time elapsed is illustrated on Figure 15. For the smoothest and safest evacuation procedure possible it is suggested that the population be divided into five groups and thereafter evacuated by five respective Civil Protection vehicles departures (d1, d2, d3, d4, d5). The number of departures may vary dependent on the intervention team's planning, as the latter, the number of available means of escape and the maximum numbers of passengers in each vehicle are inextricably linked.

For the purposes of the present study, the first departure [d1] will start as soon as 20% of the population arrive at the EAP, the second one [d2] will start as soon as 40% of the population arrive at the EAP, the third one [d3] will start as soon as 60% of the population arrive at the EAP, the fourth one [d4] will start as soon as 80% of the population arrive at the EAP and the fifth one [d5] will start as soon the last pedestrian arrives at the EAP. The time elapsed between the Civil Protection vehicles departures (d1-d4) and (d2-d5) can be utilized in order to choose the destination point and minimize the prerequisite number of pick-up vehicles.

On Figure 15 one can observe that the population's assembly takes place at quicker paces in scenario 1, which resulted in earlier departures, with the sole exception of the fourth one [d4]. The most decisive departure is the fifth one [d5]; it indicates at which point in time the settlement will have been fully evacuated at t = 28 mins (e1), whereas in scenario 2 the settlement will have been fully evacuated at t = 32 mins (e2). The fist scenario is chosen as the optimal one, as it lasts 5 minutes less than the second one. Any decrease in the response time is deemed crucial in emergencies, even though this difference might be more substantial in larger areas.

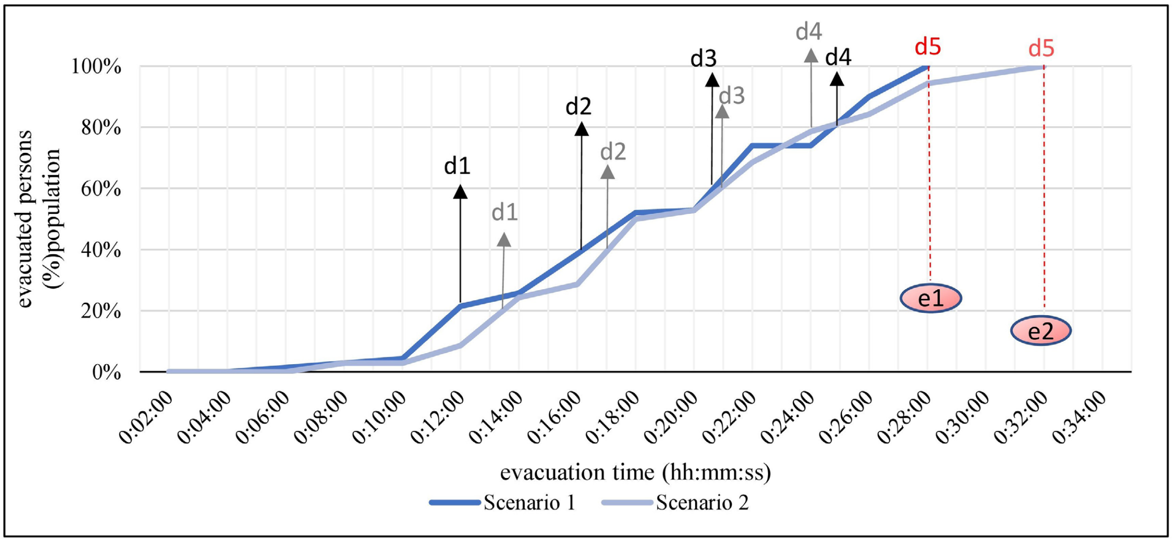

Figure 15. Comparison between scenarios diagram.

In scenario 2, 94% of the pedestrians have reached the EAP at t = 28 mins. Therefore, it can be inferred that a very small percentage of 6% of the population could delay the complete evacuation in the second scenario.

Based upon the above-analyzed in chapters 4.1 and 4.2 GIS model, the government Officials for emergencies can find the most suitable starting points for the pedestrians and intervene respectively, so as to minimize the evacuation time in scenario 2.

5. Conclusions

With the present study it has been attempted to determine the most suitable evacuation strategy for pedestrians residing in a area in a state of emergency. We have thoroughly analyzed the network, utilizing topographical measurements and GIS tools, so as to find the prerequisite evacuation time [Ti_{evac}], as well as the optimal EAP for the pedestrians.

Based upon the results of our study, the competent Authorities, the government officials and the most involved parties can acquire useful knowledge and information about isolated residences and the respective prerequisite evacuation times for their inhabitants, thus further developing and improving the Intervention Teams' contingency plans.

In conclusion, the need to develop evacuation plans pertaining to the expected reaction and response of a residential settlement's inhabitants in case of emergency on an individual level is unequivocal.

In a future study, this method could be tried and tested on a larger scale, population and acreage-wise. By the same token, a conjunction of more than one EAPs in an area of study could be attempted, which would be mandatory in a more densely populated area.

6. Discussion

Our results have shown that a fair estimate of the pedestrians' evacuation time [Ti_{evac}] is possible, taking into consideration the population's demographic characteristics, as well as the area's topographical features (altitudes, landforms, distances and evacuation routes' elevations). This strategy can contribute in making the decision to evacuate in time, when the settlement is threatened by a fast-approaching wilfire, since its redisents' response time will have already been determined.

In the mean time, a significant decrease in the total duration of the evacuation procedure can be achieved by way of choosing the optimal EAP, which in turn will reduce the time it takes the pedestrians to reach the EAP and ergo allow for their faster evacuation.

In the duration of the study, it was concluded that the senior pedestrians need a longer time to prepare for an evacuation procedure; this conclusion notwithstanding, it is evident that the position of a residence plays a more critical role in a pedestrian evacuation procedure, as it is it that determines the ground's incline and the distance the evacuees need to cover on their escape route towards the EAP. After having ascertained this, we reached the conclusion that in many cases it might take the younger residents a longer time to evacuate their settlement.

The suggested method has led to the creation of the households' classification maps based upon the calculated response time for each and every one among them, whilst in the GIS enviroment the user is able to know the prerequisite evacuation time for each individual, as well as the escape routes they will follow through a single model mapping system for escape routes.

From the two scenaria developed, we have ascertained that a very small percentage of the pedestrians were delaying the complete evacuation of the residential settlement. Therefore, in case of a natural disaster, it is advised that the Intervention Teams take initiative to prioritize helping the residents categorized under type C (see supra **Figure 12**).

In parallel, we have created a diagram illustrating the function of the evacuation time and the percentage of evacuees in the population (see supra **Figure 15**), thereby creating a method to evacuate the residential settlement in groups. From the diagram illustration, it can be inferred that a gradual evacuation of the pedestrian residents is feasible, thus avoiding any unnecessary overcrowding at the EAPs, while securing their safest evacuation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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