A GIS APPROACH TO FIRE STATION LOCATION SELECTION

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ABSTRACT:

Location science has a long historical background and the literature of location selection has expanded since it attracts much interest from researchers. As a result of many studies the location science can be classified into several sub-categories; one of which is locating emergency facilities. The determination of locating fire stations is a crucial decision for metropolitans. Reducing response time, maximizing coverage and minimizing the total cost are the most important objectives for selecting the proper location. Using Geographic Information Systems (GIS) is important since it gives an opportunity to study on maps and to have coverage matrices which show the service areas in terms of binary integers and an attractiveness matrix which shows total values of closeness to main roads, residential areas, important buildings and so on. Fire stations have to be located carefully; in an emergency situation the fire department should be able to reach its destination within 5 minutes. Hence, the coverage matrix is very important for defining the potential of alternative locations. Mathematical model is based on the coverage and attractiveness matrices with the objectives of reducing response time, maximizing coverage and the minimizing the total cost. Taking the increasing population and traffic jam and the location in the earthquake zone into consideration, the fire stations have to be found at the most appropriate location in Istanbul to facilitate the arrival at the scene as fast as possible. This paper presents a decision support system approach for locating the fire stations via the geodatabase of Kadikoy district in GIS. In this study, GIS analysis and multi-objective mathematical model were used to consider the opportunities and the threats with strong and weak sides of the possible locations.

1. INTRODUCTION

Location selection of fire stations is a crucial decision for decision makers of cities due to the potential risk of fires and the potential danger on society. On the other hand, a fire accident may cause loss of lives and properties and this can put the city governor in a rough situation. Accordingly, city governor or decision makers must take precautions against fires or service fire areas in minimum time to avoid being in such a rough situation. Thus, decision makers should minimize the risks by increasing importance level of fire station locations which attract researchers' interest on emergency location selection. Fire location selection is a subtopic of emergency service location selection and there are many studies for selecting optimum fire station location (Valinsky, 1955; Plane, 1977; Badri, 1998; Tzeng, 1999; Hewitt,2002; Liu et. al., 2006).

There are many methods and lots of problem types in location science to determine the most proper location in alternatives. Nevertheless, many of these location selections are done by simple analysis in terms of rudimentary calculation, past experience, or even predilection. Other than simple methods, more sophisticated ones have also been proposed, which make use of statistical and mathematical tools. Yet, these methods are not user-friendly in certain ways, especially when presenting the progress or results to the management. Taking the advantage of information technology, Geographic Information Systems (GIS) enable the handling of both spatial and non-spatial data, leading to its specific roles in data management and integration, data query and analysis, and data visualization (Cheng et. al., 2007).

GIS allows making analysis that determines closeness to main roads, residential areas, important buildings and so on. An attractiveness matrix gives total values of closeness analysis. In addition, GIS allows network analysis which helps to determine service areas (coverage). For instance, if you determine the speed rates of roads, it is possible to learn where a vehicle is able to reach in required travel time by using network edges and junctions.

Integrating multiple disciplines results in finding a better solution since it uses a wide range of perspectives and analyzes more criteria than a single approach and this increases the certainty of the study. In this study, GIS and multi-objective mathematical modeling were selected for determining the optimum solution. Spatial analysis and network analysis were used in GIS to find attractiveness values of grids and to find the coverage table of alternatives respectively. Mathematical modeling is the other technique which was used for finding the best solution integrated with GIS analysis. Results of GIS analysis were accepted as input of mathematical model, and the model was built on these inputs. To find the optimum solution, the model was built as a multi-objective model; since there is more than one objective. The objectives of the study are minimizing the total cost and maximizing the total coverage.

This paper presents a decision support system approach for locating the fire stations via the geodatabase of Kadikoy district in GIS.

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2. LOCATION SCIENCE

Location science has a large historical background and some experts acknowledge that the origin of the location science refers to Pierre de Fermat, Evangelisca Torricelli and Battista Cavallieri who studied on basic Euclidean spatial median problem in early seventieth century. Besides, Alfred Weber's book, Theory of the Location of Industries (Weber, 1909), is acknowledged by the experts as the first publication in modern literature. After the first publication, the interest on the location science has increased continuously and as a result of that interest location science literature expanded enormously; hence, many subtopics emerged in location science such as emergency facility selection, warehouse location selection, retail store location selection and so on. On the other hand, it can be categorized according to objectives (Farahani, 2010).

Location science has attracted more than one academic discipline, which are economics, engineering, geography, mathematics, operations research, planning and regional science (Current, 1990). All of these fields have their own approaches and it is possible to miss certain points while solving the problem; therefore, integrating multi approaches gives chance to decrease the risk of missing any points.

Since there are various types of problems, along with the need and requirement for finding the optimal solution, many different techniques have developed over the long location science history. Goal programming which is a method of operational research is used to incorporate 11 objectives and to find the best solution (Badri, 1998). There are also Artificial Hierarchy Process (AHP) (Wu, 2007) and Analytic Network Process (ANP) (Tuzkaya, 2008) techniques used for location selection science. GIS is an important tool for location selection and there are so many studies (Muttiah, 1996; Woodhouse, 2000; Noorollahi, 2008; Alexandris, 2010). Integrated methods are used in common (Kuo, 2002; Şener, 2010).

3. METHODOLOGY

Location science has a large literature that provides many applications and theoretical studies. Those academic resources give the chance to assess the existing techniques and their applications.

GIS application gives attractiveness values of the grids and coverage matrices of the alternative fire station nodes. But it is necessary to integrate the two different analyses; besides there are objectives which are expected to be optimized. The proposed methodology is to combine GIS and mathematical model to find the best solution. The results of the GIS application become the inputs of the mathematical model that give the opportunity to combine the techniques of operational research and geoinformatics. Combining more than one discipline increases the problem solving ability.

A multi-objective mathematical model is proposed to find the best optimum solution according to its objectives which are maximizing the total area under coverage and minimizing the total costs. It also provides the constraints which are locating one facility in 20 alternatives, choosing the most proper type in 4 different types of fire stations.

The selected fire station alternative should satisfy the demand of the Kadıköy district. The result was found according to objectives and constraints and that result shows the most proper location for new fire station facilities. Figure 1 illustrates the flowchart of the methodology.

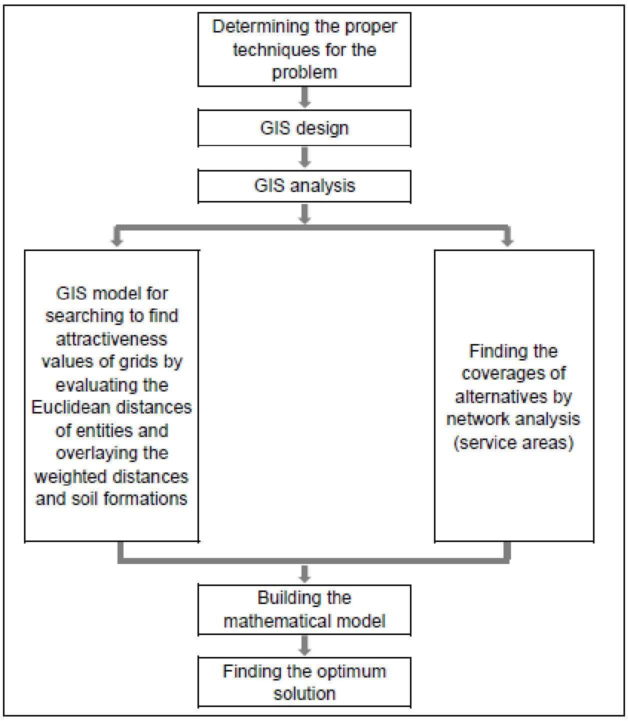

Figure 1. Flowchart of the methodology

4. GIS ANALYSIS

To illustrate the fire station location selection approach, a case study was carried out using the Kadikoy district geodabase in the GIS environment, ArcGIS 10 which is an integrated family of GIS software products for building a complete GIS. The fundamental application tools in ArcGIS Desktop are designing and building geographic databases, creating geographical analysis, making maps and performing geoprocessing.

Some of the layers of Kadikoy district geodatabase were used for fire station location selection. These layers are soil types (formations), hydrographic objects, major and arterial roads, residential streets, railroads, residence and industrial buildings, hospitals, shopping malls, fire stations, educational buildings (elementary school, high school and university) and cultural facilities (cinema, theatre etc.).

Our first step was to model the operators for searching to find attractiveness values of grids by calculating the Euclidean distances, classifying into ten classes, assigning values to classes between 1 and 10 and overlaying weighted distances, and soil types, and converting the rasters to ASCII files to get values of grids. The model was created in the ModelBuilder of ArcGIS 10 which is an application in which you create, edit and manage models is given in Appendix A.

The Euclidean distances to hospitals, educational buildings, cultural facilities and shopping malls were computed in accordance with the grid cell centers and classified into ten classes (Figure 2). Then, the values between 1 and 10 were assigned to each class with respect to closeness to the entities in the layers. Thus, grid cells with higher values reflect the more suitable locations (Figure 3). The entities of which Euclidean distances were calculated are the most important ones in social life. It is possible to choose other entities if their data is available. Since the residential and industrial buildings are spread unsystematically in Kadikoy, Euclidean distances haven't been determined for them. The extent of the study area was limited by the boundaries of Kadikoy and the chosen cell size is 120 meters.

Determining the cell size is important to reach acceptable results; thus the cell size is accepted according to the publication of (Liu, 2006). Liu accepted 200 meters for the cell size and it is used for their analysis. The cell size of 120 meters was found empirically in this study and it is suitable under constraints of computing and data preparation time and the capacity of the solver of mathematical model.

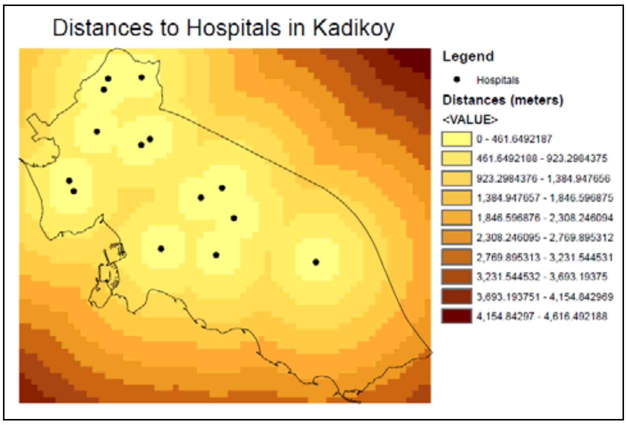

Figure 2. Euclidean distances (meters) to hospitals in Kadikoy

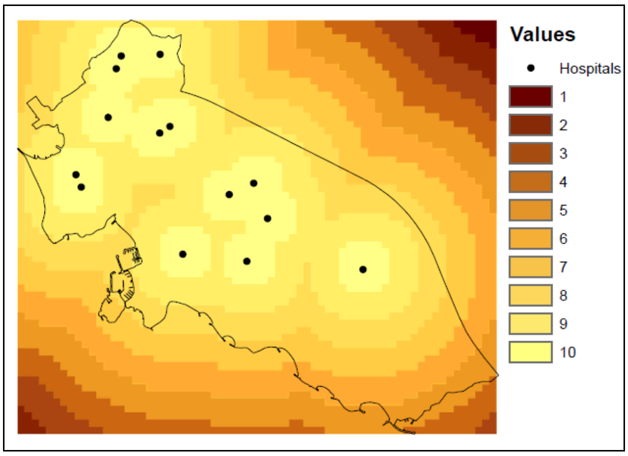

Figure 3. Assigned values to distance classes of hospitals

The classified distances with values and soil types were weighted and overlaid, and thus the attractiveness values were obtained (suitability of locations). The attractiveness values are between 0 and 10. Zero value is assigned to restricted locations. Locations with higher values are more suitable than locations with lower values. Four values are in Kadikoy district and six values are outside of Kadikoy boundary. Soil type values were determined according to the capacity of the soil for construction pressure (suitability of settlement) [1]. The attractiveness values of grids are illustrated in Figure 4.

The following percentages of influence (weights) were given

- Distance to hospitals: %30
- Distance to educational buildings: %25
- Distance to cultural facilities: %25
- Distance to shopping malls: %10
- Soil types: %10
  - Tuzla Formation: 10
  - Trakya Formation: 10
  - Kartal Formation: 10
  - Baltalimanı Formation: 9
  - Alluvium Formation: 1
  - Unnatural filling: 0 (restricted)

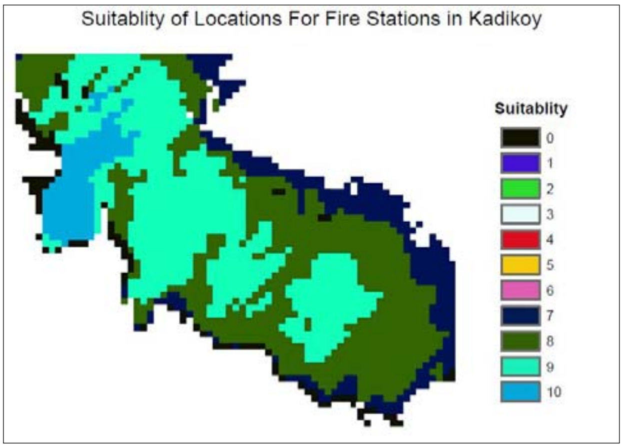

Figure 4. The attractiveness values of grids

Reaching accident areas in 5 minutes is crucial for inhibiting the losses and reducing the response time from 8 minutes to 5 minutes is also accepted in as primary intention (Liu, 2006). Ince's study is another example for the importance of determining 5 minutes for response time (Ince, 2009).

In the last step of GIS analysis, we created a series of polygons representing the distance that can be reached from an alternative node within 5 minutes by network analysis. These polygons are known as service area polygons. We calculated 5 minutes service area polygons for 20 alternatives selected as in 250 meters buffer for major and arterial roads. Two alternatives are existing fire stations in Kadikoy. Estimated speed rates (30, 40, 50, 60 km/h) were assigned to major and arterial roads and residential streets. One way restriction was ignored. Figure 5 illustrates 20 alternatives and one of the existing fire stations' service area in Kadikoy. The polygons were converted into raster and then ASCII files to get service areas in terms of binary integers for mathematical model input.

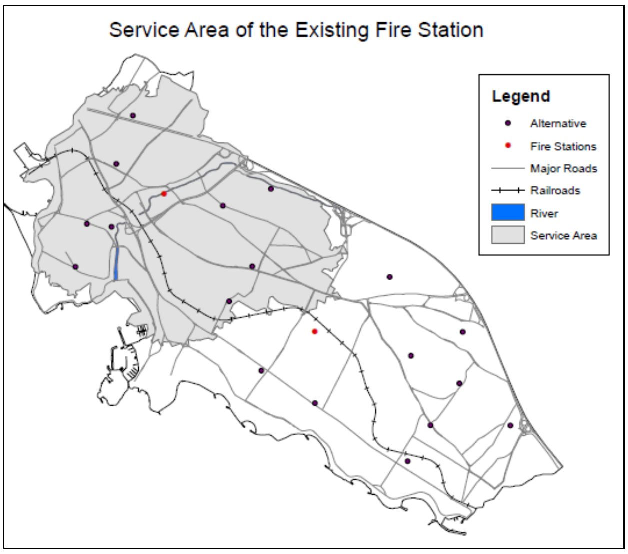

Figure 5. 20 alternative nodes and one of the existing fire stations' service area

5. THE PROPOSED MATHEMATICAL MODEL

The proposed mathematical model is an example of a multi-objective model for selecting the optimum location for fire station in 20 alternative locations which aim at reaching fire locations in 5 minutes.

The mathematical model has two objectives which are minimizing total cost and maximizing total number of under coverage grids. Objectives were not weighted; thus, two objectives have the same importance level.

The model is trying to find the best location for a fire station facility and there are 4 different types of fire stations which have different setup cost and different fire fighting capacities (Table 1). Fire fighting capacities are important to cover total demand of fire fighting service of the Kadıköy district.

Fire Station Type	Total Cost	Fire fighting capacity
1	50	100
2	150	300
3	350	400
4	700	500

Table 1. Total cost and fire fighting capacity of fire station types

The study area was separated to 3886 grid which should be serviced by fire stations because of its fire accident risks. There are 20 fire station facility alternatives and also 4 station types for these alternatives. The mathematical model is aimed to find the best solution according to objective functions under the constraints and that minimum cost and maximum grid coverage is expected from the selected alternatives.

5.1 Variables, Indexes and Notations

i = index for alternative areas' fire risks which are to be serviced
j = index for alternative sites for potential fire station
t = index for alternative fire station types
Ct = total setup and operation cost
Et = total fire extinguish capacity of facility t
Ai = attractiveness of area i
x(i,j,t) = decision variable
coverage(i,j) = the table which consists of the area coverages of alternative locations

5.2 Objectives

The first objective is for minimizing total cost.

$$\text{Minimize } z1 = \sum_{i=1}^{3886}\sum_{j=1}^{20}\sum_{t=1}^{4} x(i,j,t) * Ct \qquad (1)$$

The second alternative is maximizing the grid coverage. Coverage matrix is multiplied with decision variable; hereby, the second objective is defined.

$$\text{Maximize } z2 = \sum_{i=1}^{3886}\sum_{j=1}^{20}\sum_{t=1}^{4} x(i,j,t) * Coverage(i,j) \qquad (2)$$

5.3 Constraints

There are 4 fire station types which can be chosen. Only one type station can be selected for alternative potential fire stations. Each facility types have different fire fighting capacity and cost value.

$$\sum_{i=1}^{3886}\sum_{j=1}^{20}\sum_{t=1}^{4} x(i,j,t) \leq 1 \;\; \forall j \qquad (3)$$

The selected fire station should meet the fire demand of Kadıköy. In the year of 2011, there were 2984 fire accident in entire Istanbul, and 4% population of Istanbul [2] lives in the Kadıköy district. Accordingly it is accepted that the new fire station should cover the 10% of the total demand which are 299 fire accidents. Each fire station types have different capacity to reach and interfere to fire accidents in same time.

$$\sum_{i=1}^{3886}\sum_{j=1}^{20}\sum_{t=1}^{4} x(i,j,t) * Et \geq 299 \;\; \forall j \qquad (4)$$

Model is trying to determine the best one in alternatives; therefore, the equation provides to select one of them.

$$\sum_{i=1}^{3886}\sum_{j=1}^{20}\sum_{t=1}^{4} x(i,j,t) = 1 \;\; \forall j \qquad (5)$$

The decision variable is a binary variable and it can only have the values 0 and 1. If the decision variable takes the value of 1 that means the alternative is proper for setting up a fire station and the value of 0 means that the alternative does not support the requirements, thus, it is not a proper location. The decision variable cannot have a negative value.

$$x(i,j,t) \geq 0 \qquad (6)$$

6. RESULTS

The selected fire station alternative should satisfy the demand of the Kadikoy district. The result is found according to objectives which are maximizing coverage and minimizing total cost, and constraints. The model tries to maximizing the total coverage of grids but also it considers the attractiveness values of grids. The multi-objective mathematical model is built to find the best solution and the most appropriate location for the new fire station facility.

The result of the mathematical model indicated that the best alternative location for the fire station is the area valued as 9 which is calculated by the closeness to the major roads, hospitals, educational buildings, cultural facilities and the shopping malls, and the soil type weights. The soil type of the best alternative is the Trakya formation. There should be established the second type of fire station facility to cover total demand of the Kadikoy district. The 5 minutes service area (coverage) of the best alternative is shown in Figure 6.

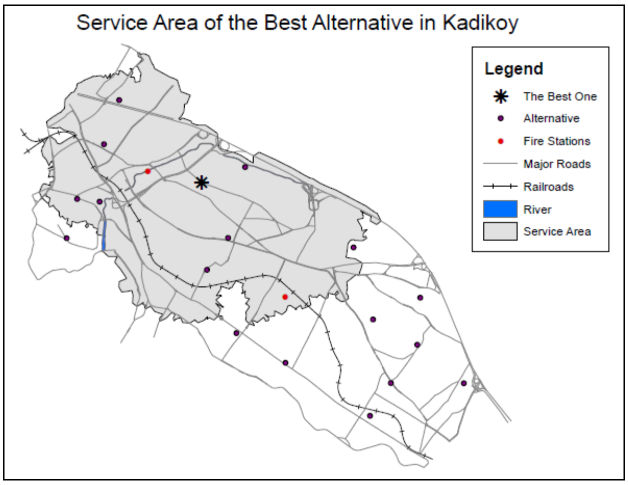

Figure 6. 5 minutes service area of the best alternative.

7. CONCLUSION

The number and location of fire stations significantly influence the efficiency of emergency response during fire accidents. The fire stations have to be found at the most appropriate location in Istanbul to reach the scene as fast as possible considering the increasing population and traffic jam and the location in the earthquake zone. This application is inclined towards disaster management. This paper has presented an approach to optimally selecting fire station location by integrating GIS with a multi-objective mathematical model.

Some extensions to this study can be done in our future research. One of the difficulties in applying the model was developing the travel times in the networks analysis. The travel times can be given more accurate considering the traffic jam and one way restriction. The number of alternatives can be increased in order to provide the variety of the locations. However the cell size of the grids can be decreased to have more detailed information, setting a smaller cell size will not always have more detailed information in the raster results; you will just have more cells of the same value which may affect your display and calculation speeds.

This process serves as a prototype for the development of a decision support system combining GIS with multi-objective mathematical model. Such a system will be valuable in decision making for emergency facility location and other real-life spatial optimization problems.

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APPENDIX A. THE MODEL FOR CALCULATING ATTRACTIVENESS MATRIX