International Journal of Emerging Research in Management &Technology ISSN: 2278-9359 (Volume-5, Issue-4)

Research Article **April 2016**

Fuzzy Modeling to Determine the Optimum Location of Fire Stations, with Network Analyst and ANP (case study: sixth district of Tehran)

Jahanbakhsh Balist*, Saeed Karimi, Isar Noraisefat, Abbas Mirkarimi
University of Tehran, Tehran,
Iran

Abstract—

In modern world, citizen safety is on one the most important issues which is related to various factors. In urban environments, there are many issues which can disturb the balance and fires are one of these issue. Planning is an important aspect to reduce their impacts. In this research, we used MCDM (multiple criteria decision making) techniques and GIS (geographical information systems) for optimum site selection of fire stations. with the help of ANP (analytical network process) , 12 criteria (nearness to hospitals, nearness to religious places, nearness to medical emergency centers, nearness to hydrants, nearness to crisis management centers, nearness to electricity distribution centers, nearness to elementary schools, nearness to secondary schools, nearness to main roads, nearness to populated areas, distance from existing stations, nearness to fuel distribution centers) are prioritized based on expert opinions and pair-wise comparisons , and then with the help of model building tools, different layers are standardized, weighted and overlaid. Finally 3 maps of sixth district of Tehran city are chosen, which can be used for constructing new fire stations. ANP is a suitable tool for choosing optimum points of construction.

***Keywords**— Firefighting, ANP, network analyst, model builder, GIS*

I. INTRODUCTION

With respect to rapid population growth and illogical urbanization and based on increased public service needs, government interventions and improved planning for social justice and equitable service accessibility, is a necessity [29]. Planning process is an effort to establish a suitable framework, in which planner can act to reach the optimal solution [17].

In urban environments, planners deal with optimal distribution of land use and service centers [2]. One of the most important goals of urban planner is to create an urban environment in which all of citizens can easily access to urban services [18]. Spatial distribution of services with respect to future urban development and changes, will satisfy citizens [11]. In this regard, planners try to present suitable land allocation patterns for urban usages and appropriate site selection, in order to provide welfare and safety in cities [29]. In fact city safety consists of a set of measures which are used for prevention or mitigation of casualties and financial negative impacts of natural and unnatural events, such as floods, fires, earthquakes, car accidents, etc [10]. Fire stations are very fundamental and important structures in cities [23] which quick, on time and inexpensive access to them is very critical in every society, modern urban communities specially [6]. Lack of proper distribution of stations and their limited operational radius, are the most important problems in their service delivery [13]. Not only site selection reduces wasting costs, but also it guaranties optimum performance of service centers in urban systems. Presence of high spatial overlap between some service centers and lack of sufficient service centers in some other areas, represents unfair site selection of safety service centers in a city [1]. The most important issue for planners and managers of urban affairs is to decide properly in complex situations [30]. GIS (geographical information system) is a functional and administrative system for planning in these fields. Kao and Lin 1966 suggest that with respect to GIS vast capabilities in decision making problems and its functions for overlaying information layers, this system is the best option for site selection process. This system can save, retrieve and analyze data in order to facilitate decision making process for planner. therefore, with respect to land use in cities with suitable criteria (such as local populations, spatial distribution of service centers and their relative distances and quick access to them), we need to perform appropriate planning and decision making process to establish service centers and GIS applications are very useful in this regard. There are plenty of methods for site selection and assessment of facility spatial distribution such as ANP. Between different methods, ANP is more efficient, since it is capable to use various criteria for suitable decision making and prioritization of criteria impacts [19]. Before performing site selection process and before map overlaying, we need to standardize criteria. It means that for all of our layers, we must use a scale in our decision making, by which we can easily incorporate our layers. In this regard fuzzy logic is a suitable option [12]. If we use modeling for site selection of urban facilities and utilities, the results would be improved. Model is a projection of reality which can express complex feature of real world in a simple form, it is also a conception of reality which can be used for interpreting world complexities in an understandable manner [27]. However, we obviously need GIS for spatial modeling of relations between various functional cetners [24]. Models based on GIS have four important capabilities (i.e. data entry, data management, data analysis and providing proper outputs) which makes it easy to understand spatial relations between different points of a map [5]. We have 3 level of analysis in GIS: information gathering, information analysis based on statistical and mathematical calculations, modeling and anticipating trend of event changes and proposing suitable actions. In these models, urban utilities and facilities are chosen in a cost effective manner and with respect to optimum usage. In GIS-based models, for any kind of analysis, presence of spatial information about service centers and urban facilities is a necessity. So before performing analysis, we must be assured about the presence of suitable information banks [20].

In Iran and all over the world, there are various site selection studies about our research field. Reviewing previous studies can help us to find the best research methodology, best measures and site selection techniques. In the following we briefly mention to some of them:

Molaie et al., in an article named (site selection of fire stations for emergency relief based on GIS and MCDM models), used criteria such as nearness to residential areas, access to communication roads, nearness to business centers, distance from health care centers and nearness to industrial districts, and incorporated information layers; they concluded that north-east and south-west of 8th district of Tehran have more priority for establishing fire stations [21].

Adeli et al., in a study named (site selection of fire stations in Gorgan city with geographic information system), analyzed the desirability of station construction with respect to neighborhood units (i.e. consistent neighborhood, inconsistent neighborhood and semi-consistent neighborhood). They used ANP and layer overlapping in GIS for site selection, and AHP for criteria weighting. They used response time of 1, 2, 3 and 4 minutes for evaluation of station coverage [1].

In January 2007, ESRI Company performed a related study with this title: site selection of fire stations and their development with GIS [9].

Chevalier et al, in a research named (site selection of fire station network with an integrated approach in Belgium), used spatial decision support system and parameters such as population distance and density and evaluated fire station potentials for fire accident responses. They used performance radius of 8 minutes and accident coverage rate of 90%. Their results shows that with standard performance radius, 60 fire stations in this country can cover 67% of possible events [8].

Murray, in an article named (spatial location optimization of fire stations in California), determined 9 minutes as the standard response time to fire events. He used strategic planning for site selection of new stations and with the help of Buffer Tool, he found suitable distribution of new stations [22].

Lai et al, in a study named (implementation of fire station location planning based on AHP and GIS in China) performed site selection for these stations. In this research, standard time and standard distance from fire station are found to be respectively 5 minutes and (4to7) kilometers [16].

Nouraie, in a research named (modeling of garrison site selection with GIS and AHP), presented an optimized step by step method for finding the best location of garrisons [26].

Karimi et al, with emphasis on parking structures site selection, modeled the site selection process of urban utilities with GIS. In this research, they presented a suitable pattern for optimized site selection of public parkings with GIS and compared different weighting methods for various layers [15].

Pourahmad et al, performed hospital site selection modeling with Fuzzy logic and incorporated AHP and Topsis in ARC GIS environment. Not only they evaluated hospital site selection process in Tabriz, Iran with respect to qualitative measures, but also they presented a suitable model for this city [27].

II. MATERIALS AND METHODS

Our research is a descriptive-analytical study. We obtained data and information through library resources, various documents and field observations. We used site selection instructions for urban service centers (fire stations) in our software and also related scientific materials in this field.

Study area

6th district of Tehran is one of relatively old districts of this city, which covers almost 3.3% of its area. From north, it is restricted by 3th district, from east it is restricted by 7th district, from south it is restricted by 12th, 11th and 10th districts and from west it is restricted by second district of Tehran. This district is located in city center area and it contains many official and service establishments with various important scale of operations (cross-regional, metropolitan and national). On the other hand, this region is located in geographical center of Tehran and has proximity to old town center (i.e. Tehran's Grand Bazzar, Arg Square and Toop Khaneh), all of these features make this area so important and strategic. It contains 220000 people, 4 fire stations and roughly its area is 20 Km^2 .

Methods

Fire station site selection, depends on various measures and if we neglect these measures, time and money would be wasted and suitable locations won't be found. In such situation, if accidents occur, improper site locations facilitate the potential crisis. Therefore in order to perform site selection process for these critical centers, we must consider the most important measures and criteria. in this research, 12 criteria (nearness to hospitals, nearness to religious places, nearness to medical emergency centers, nearness to hydrants, nearness to crisis management centers, nearness to electricity distribution centers, nearness to elementary schools, nearness to secondary schools, nearness to main roads, nearness to populated areas, distance from existing stations, nearness to fuel distribution centers) are considered for choosing the best location of fire stations.

In present study, first we prioritize abovementioned parameters with ANP and then in ARC GIS environment, we generate information layers and standardize them with fuzzy logic. Layers will be multiplied by obtained weights from ANP and layer overlaying is performed by fuzzy operators.

ANP method: Analytical network process

ANP is one of MCDM techniques which was presented by Al Saati in 1980. this method is actually an extension of AHP (analytical hierarchy process), since one of the most critical weaknesses of AHP was about its basic assumption that measures act independently, hence in AHP their interrelations were neglected, although is reality such setting rarely happens. Researches had many problems with AHP, so ANP was introduced to address them. The main advantage of this newer technique is about its network structure, since in ANP we can consider interrelations and interactions between different measures in different and same levels of our calculations. ANP is composed of four important stages:

Stage 1: in this stage we perform pair wise comparison of measures and determine their relative weights. This stage is similar to corresponding stage in AHP, i.e. relative weights of measures are obtained by their pair wise comparison.

Stage 2: in this stage, we put obtained weights in a bigger matrix (super-matrix). Super matrix contains all network clusters and nodes and shows their interrelationship, we refer to this matrix as initial matrix.

Stage 3: in this stage, we calculate cluster weight in order to calculate initial matrix weight. After cluster weights matrix is generated, we can generate initial super matrix by multiplying cluster weights matrix to initial matrix. The resultant matrix is called random matrix.

Stage 4: finally we generate super matrix. For this purpose we must multiply weighted super matrix by itself (n times) until we get super matrix. In this matrix, column amount are the same. If more than one matrix is generated, then we must use this formula:

$$\text{Lim } n \to \infty \left({}^{1}/_{F}\right) \sum Wi$$

In order to calculate the final weight [24].

Fuzzy logic model

In classic sets, all member of a set belongs to their set. However in fuzzy sets, members belong to a set with degrees of membership. Degree of membership is a number between 0 and 1. So fuzzy logic assigns a value between 0 and 1 to each member as the membership value.

Site location parameters have somehow a fuzzy nature. For example factors related to distances from some kind of topographies, are fuzzy sets and each pixel, based on its distance from topographies, has a different degree of membership in these fuzzy sets. Membership criteria for pixels to be in desired sets, is a number between 0 and 1. These values are determined by expert opinions. If all of the problem parameters are defined by fuzzy sets and their membership values are suitable, then we can use proper fuzzy operators to incorporate them. Type of fuzzy operators depends on impressionability of different factors from each other and operator final effect on parameters set. Some effects of fuzzy operators are increasing, while others are decreasing. In the former, final membership degree of a pixel will reduce and in the latter it will increase.

Fuzzy operators are: fuzzy AND, fuzzy OR, fuzzy Algebraic sum, fuzzy algebraic product and fuzzy Gamma operation which are used for incorporating different factors.

αA (x) represents the weight or membership value of a pixel in a fuzzy set. Note that with performing fuzzy operators, pixel units of an output map contain membership degree.

Fuzzy AND operator: this operator is defined as below:

$$\alpha_{A \cap B}(x) = MIN(\alpha_A(x), \alpha_B(x))$$

Fuzzy AND operator, extracts the minimum membership degree of pixel units and apply it to final map. When two or more factors are necessary to prove an assumption, fuzzy AND operator would be suitable.

Fuzzy OR operator: this operator is defined as below:

$$\alpha_{A \cup B}\ (X) = MAX(\alpha_A(X), \alpha_B\ \alpha(X))$$

This fuzzy operator extracts the maximum membership degree of pixel units and apply it to final map. When site selection measures are rare and when the presence of positive factors is sufficient for demonstrate utility, we will use this operator.

Fuzzy Algebraic sum operator: this operator is defined as below:

$$\alpha_{product}(x) = \prod_{i=1}^{n} \alpha_i(x)$$

With this operator, fuzzy membership values in output map decrease and tend toward 0. Unlike two abovementioned operators, in this operator, all membership values of input maps, have influence on output map.

Fuzzy Algebraic product: this operator is the complementary operator of fuzzy algebraic sum and is defined as below:

$$\alpha_{sum}(x) = 1 - \prod_{i=1}^{n} (1 - \alpha_i(x))$$

With this operator, fuzzy membership values in output map increase and tend towards 1. When some parts of evidence and factors reinforce each other, we use this operator.

Fuzzy Gamma operation: this operator is defined as below:

$$\alpha_{gamma\_operation}(x) = (\alpha_{sum}(x))^{\gamma} . (\alpha_{product}(x))^{1-\gamma}, \quad 0 \le \gamma \le 1$$

If we choose a correct and wisely value of γ between 0 and 1, we will get an output value which shows the flexible consistency between increasing and decreasing trend of two fuzzy operators. We use Gamma operator when some evidence are increasing and some others are decreasing.

With respect to fuzzy features and fuzzy operators, problem parameter description and their corresponding weights will have enough accordance with reality. We can determine membership functions with various methods. In fuzzy site selection applications, we usually use fuzzy operators for incorporation of spatial data however, if we want to find the exact output of our model, we must design a fuzzy systems in which factor maps as system inputs, must convert to fuzzy sets. Then based on predetermined rules, maps will be integrated [7].

Model Builder

Model builder is a tool for generation, edition and management of models. With this tool, we can apply different ARC GIS tools in a set and display different stages of process in a model. This tool is located in Standard menu of software. After beginning of modeling process, a window will open, and we must drag our necessary tools to this window and perform related operations (fig1).

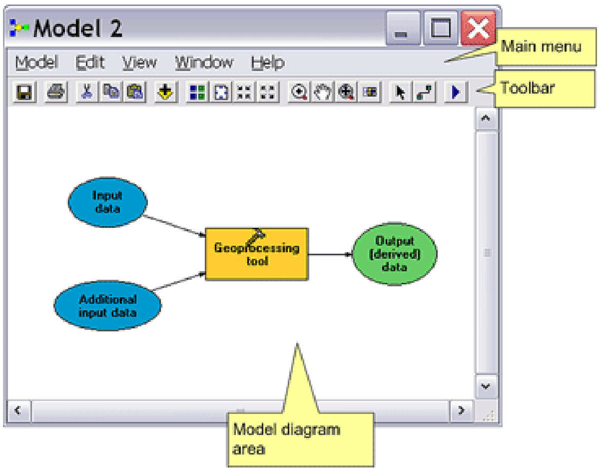

Fig (1): model builder tool window

Network analyst

Network Analyst is a tool in GIS in which, topographies such as road network can be analyzed. There are many sub-tools in network analyst which can be used for different analysis. In this research we used Service Area tool. For using this tool, based on the type of streets (one way - two way), road network must be converted to Network Dataset format. Then we must define utility layer (in our case, fire station layer (existing and proposed stations)) in order to capture service delivery scope for different time frames. Here, time refers to an interval of time in which fire trucks receives to fire scene.

III. RESULTS AND DISCUSSION

In below, our results are presented based on different stages of analysis. In this research, different criteria are used for finding the optimum locations of fire stations. Prioritization of these criteria is performed with the help of expert opinion and Super Decision Software (table1) and the results of our prioritization is shown in table2. With respect to software output, the most significant criteria is (distance from existing stations), the second most significant criteria is (nearness to road network) and the least significant criteria is (nearness to religious places).

Table I Results of Pair Wire Comparison in ANP

		distributional	**Services**							**Arrival**			
		Distance from existing stations	Proximity to primary schools	Proximity to secondary schools	Proximity to religious centers	Proximity to populated areas	Proximity to hospital	Proximity to center of power distribution	Proximity to fuel distribution centers	Proximity to network	Proximity to fire pump	Proximity to center of medical emergency	Proximity to center of crisis management
distributional	Distance from existing stations	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933	0.4933
services	Proximity to primary schools	0.0487	0.0642	0.0622	0.0542	0.0552	0.0606	0.0708	0.0795	0.0808	0.0810	0.0605	0.0757
	Proximity to secondary schools	0.0318	0.0624	0.0622	0.0624	0.0578	0.0679	0.0578	0.0688	0.0569	0.0666	0.0473	0.0546
	Proximity to religious centers	0.0109	0.0182	0.0169	0.0198	0.0196	0.0204	0.0174	0.0210	0.0185	0.0164	0.0208	0.0204

	Proximity to populated areas	0.0398	0.0624	0.0664	0.0778	0.0787	0.0506	0.0601	0.0449	0.0465	0.0574	0.0873	0.0550
	Proximity to hospital	0.0318	0.0433	0.0409	0.0404	0.0380	0.0481	0.0472	0.0432	0.0512	0.0434	0.0423	0.0411
	Proximity to center of power distribution	0.0163	0.0295	0.0302	0.0279	0.0336	0.0298	0.0279	0.0235	0.0240	0.0213	0.0261	0.0341
	Proximity to fuel distribution centers	0.0163	0.0305	0.0318	0.0279	0.0276	0.0331	0.0293	0.0296	0.0326	0.0245	0.0262	0.0296
arrival	Proximity to the network	0.1402	0.0880	0.0898	0.0969	0.0489	0.0969	0.0783	0.0783	0.0783	0.0773	0.0969	0.0773
	Proximity to fire pump	0.0369	0.0469	0.0281	0.0267	0.0489	0.0274	0.0391	0.0391	0.0391	0.0386	0.0267	0.0488
	Proximity to center of medical emergency	0.0811	0.0402	0.0442	0.0454	0.0489	0.0390	0.0391	0.0391	0.0391	0.0386	0.0267	0.0329
	Proximity to center of crisis management	0.0525	0.0205	0.0335	0.0267	0.0489	0.0323	0.0391	0.0391	0.0391	0.0468	0.0454	0.0386

Table II Weight Obtained For Different Criteria in ANP

Criteria	**The final weight of the layers**
Proximity to fireplug	0.037271
Proximity to center of medical emergency	0.059697
Proximity to center of crisis management	0.045083
Proximity to the network of road	0.110496
Proximity to hospital	0.038218
Proximity to center of power distribution	0.022156
Proximity to fuel distribution centers	0.023154
Proximity to religious centers	0.015048
Proximity to primary schools	0.059028
Proximity to secondary schools	0.045635
Proximity to populated areas	0.050829
Distance from existing stations	0.493386

Fig. 2 shows model builder tool. We can observe that all performed processes and utilized tools are shown in an integrated manner.

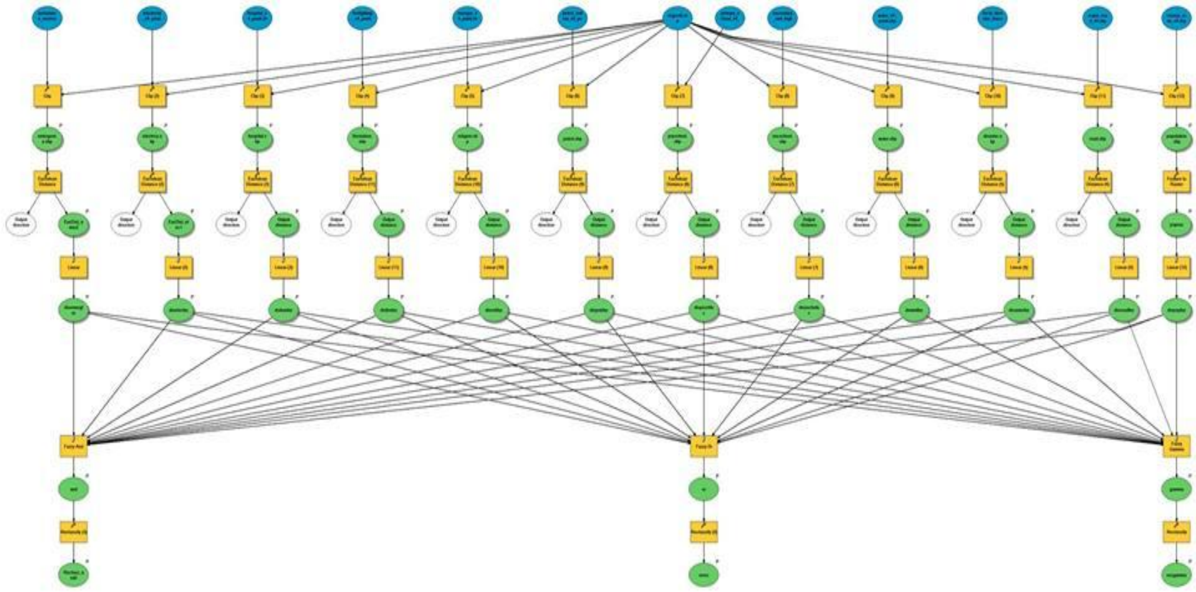

Fig2: model building diagram

After weighting, different standardized layers with the help of fuzzy functions (Fig3), are overlaid (Fig4) and Y=0.5 is chosen as the suitable result compared to other operator results. This operator is a combination of fuzzy algebraic sum and fuzzy algebraic product operators. If its coefficient is 0, the result is similar to Fuzzy Algebraic sum operator and if its coefficient is 1, the result is similar to fuzzy algebraic product operator. For achieving to a logical result in this research, we used 0.5 as the coefficient and finally we compared different operator results and used ANP in order to find 3 point as the optimal locations.

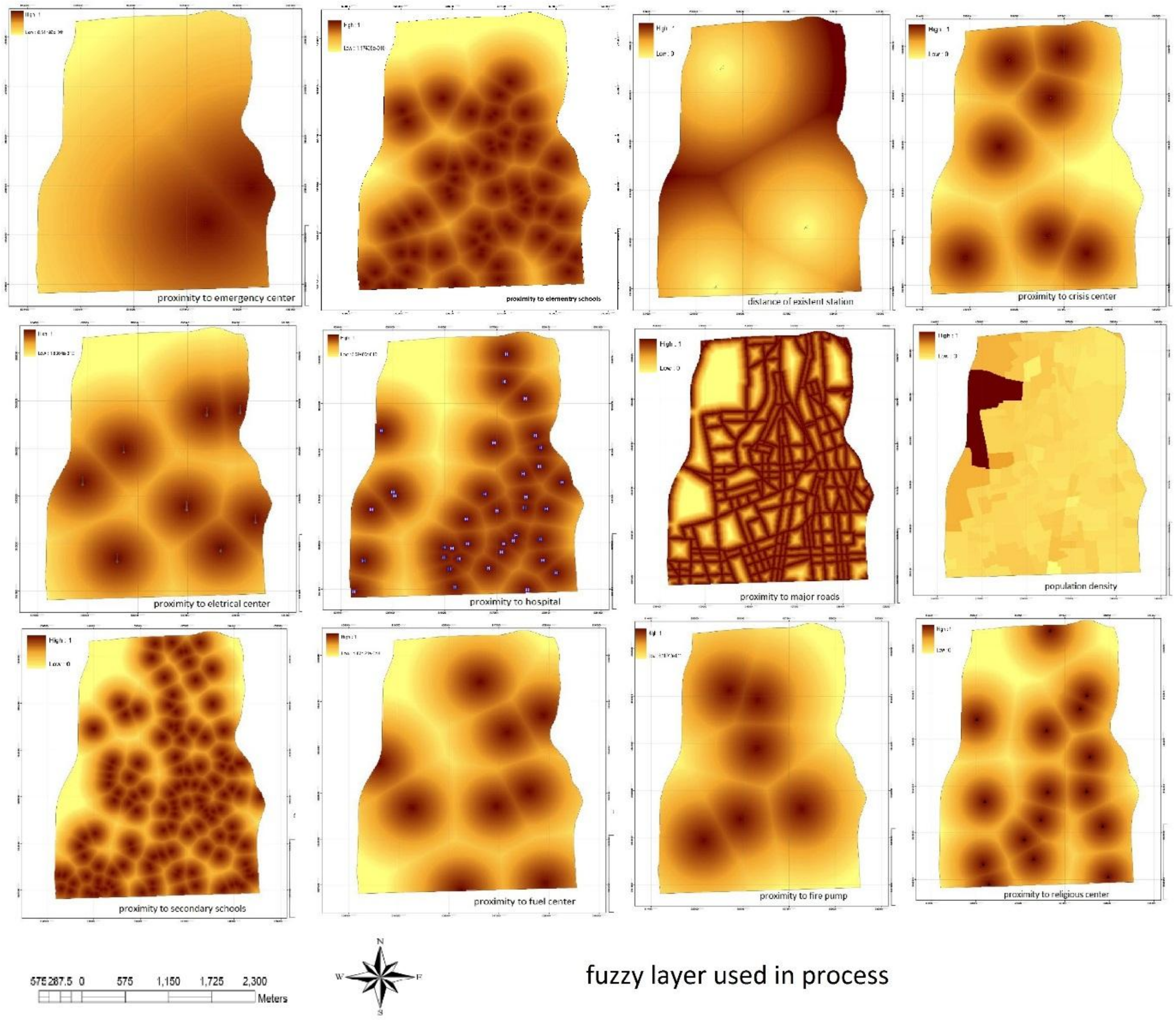

Fig3: different standard layers used in site selection process

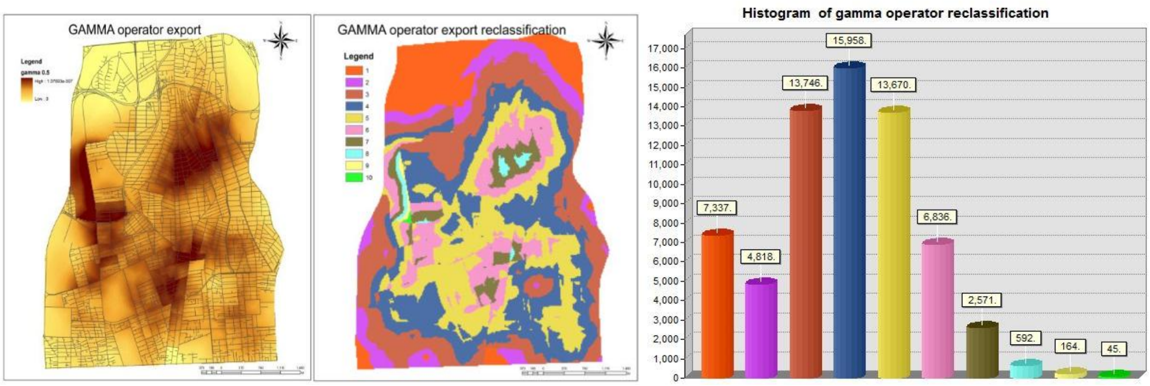

Fig4: Gamma operator results combined with Network (right), classification of Gamma operator result (middle) and the histogram of different power categories of Gamma operator result (left).

Network analysis

In this research, we used Network Analyst Tool for analyzing the network. So road network of 6th district of Tehran converted to Network format in Arc Catalog. Then it was added to ARC MAP environment and with the help of Network Analyst tool, we created service delivery scopes for existing and proposed stations (we overlaid different layers which are generated in previous steps). We can see 3 main sites in the map (Fig5).

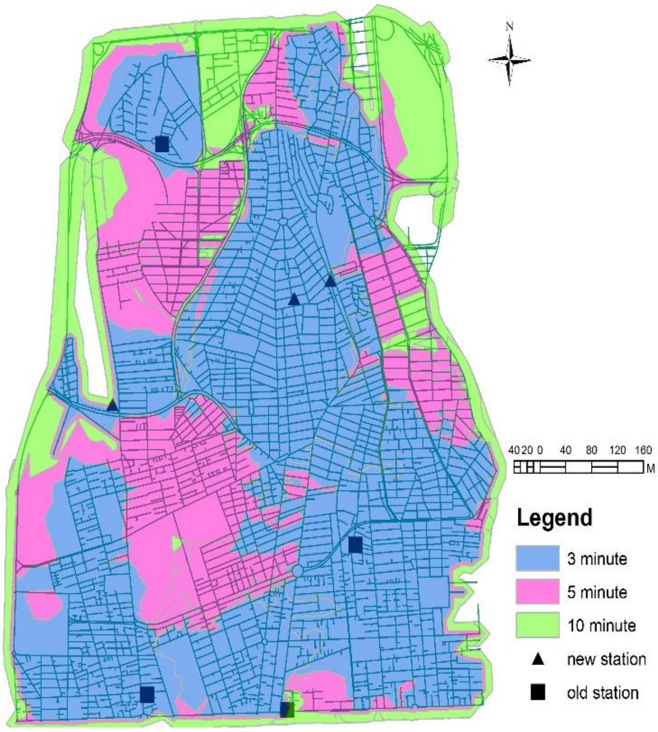

Fig5: 3 main sites for firefighting services

IV. CONCLUSION

Our results indicate that using GIS is important and beneficial in site selection of urban services and utilities, since GIS is a powerful tool for spatial modeling and can help managers in urban crisis planning. In this article, we used fuzzy modeling in GIS and ANP for site selection of net fire stations of 6th district of Tehran city. We used ANP for criteria prioritization and then we standardized layers with the help of model builder tool in ARC GIS. For layer overlaying process, we utilized Fuzzy Gamma operator, fuzzy And operator and Fuzzy OR operator and results indicates that Gamma operator is more logical. We used Model Builder Tool for integration of different processes which are used in this research. Results of fuzzy logic shows the area capability for establishing new stations, after reclassification, 3 points was chosen as candidate areas. 4 stations are available in this district and if we add 3 new stations, we will have 7 operational stations. Finally, in order to assess the coverage of these 7 stations, we used network analyst. For this purpose, we generated 3 service delivering areas in road network, with 3, 5 and 10 minutes as response times and evaluated the coverage of existing and proposed stations. results indicates that for response times of 3 and 5 minutes, some parts of our district are encountered with the lack of sufficient services but for response time of 10 minutes all of the district will be covered.

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