SOLVING FIRE DEPARTMENT STATION LOCATION PROBLEM USING MODIFIED BINARY GENETIC ALGORITHM: A CASE STUDY OF SAMSUN IN TURKEY

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Abstract

Fire and traffic accident are the most common problem in our daily lives. Fire department location for the purpose of easy response and recovery is a significant problem today. The best location of a fire department station determines the rate of recovery of many injured people after traffic accident, fire outbreak, and so on. In this paper, we considered the best location of fire stations. In addition, we also considered where the station is setup. Surveying problem is modeled as a mixed integer programming. It is solved by modified binary genetic algorithm, coding with GAMS. Modified binary GA is different from known GA with respect to binary decision variables. Due to this problem, initial value of the objective function was obtained from known GA. Then finally, the best result was achieved from binary GA.

Keywords: Location Problem, Binary Genetic Algorithm, Fire Department Location

Introduction

Today, search and rescue operations are made by various institutions and organizations. Also, search and rescue operations also vary from country to country. Apart from disaster and emergency situations, fire departments usually conduct their saving operations in urban areas. However, it is important to give emergency assistance properly and on time so as to save the lives of the wounded. Emergency services are usually given using fire engines and ambulances. For example, after a damaging traffic accident occurs, the saving operations for the wounded that got stuck in the car are done by the fire department. After the saving operations, the wounded are taken to the hospital by an ambulance. Therefore, the fire engine should arrive at the crash site earlier than or at least together with the ambulance. This makes it possible for emergency medical care to be given during this process. Therefore, the location of fire department facility is as important as the allocation of ambulance services. In addition, there is high mortality rate of the wounded that were not properly attended to on time.

Apart from modern urban life, fire department services are also a part of daily life in the rural areas. Fire departments perform various rescue operations from traffic accidents to as little as rescuing a pet from the top of the tree. The basic requirement for the improvement of rescue operations is to determine the optimum place for fire department facilities. In a dangerous situation, it is a race to get to the scene, rescue the wounded, prevent any possible fires, and extinguish any fire outbreak. However, fire department facility location is important to minimize the resulting effect of these adverse situations. It is well-known that public services have limited budget. Today, apart from the private sector, public services also have the need to lower the expenses while having the same quality. Fire department services as a public service are services that should not compromise its quality and the requirements that are given in regulations.

Facility location problems are known as hard to solve problems. Thus, this kind of hard to solve problems requires the use of computer technology. The development in computer technology brings new conveniences to the solution approaches. In this study, an interface that will facilitate data entry to the computer solver program was also developed. With this newly developed interface, the coefficients of the variables in the solver program were easily replaced. As an example of integrated development environments that are used in computers to solve mathematical problems, we can give General Algebric Modeling Systems (GAMS). GAMS is a mathematical modeling programming environment. Problem is written in an analytical form and coded using computer programming language in GAMS IDE. Furthermore, the appropriate solver for this model's solution can be chosen in this IDE. Data is entered with program code from the inner or outer environment. In the inner environment, data is coded as a parameter or table in IDE environment, while problem is coded in an analytical form. In the outer environment, problem is coded using an analytical form and then data is saved in MS Excel spreadsheet or any other third party program. The data connections to GAMS IDE are made with gdxxr.exe third party software. In addition, solver can change according to mathematical model being linear, non-linear, or quadratic. Thus, the mathematical model developed in this study is linear.

Literature Review

Facility location problems are first seen in literature as assignment problems. However, this is known as Classic Weber Problem and this depends on the principle of minimizing total distance in a euclidean space. It was first found by Pierre Format (1601-1655) as the minimization of total distance problem. Also, it was solved by the Italian mathematician Evangelista Toricelli (1608-1647) who was a student of Galileo. This problem has been examined by mathematicians until recently. Recently in a study, Zacharias (1913) reexamined this problem. In his study, Kuhn (1962) made the best descriptive work of Zacharias' (1913) work. Today, facility location problems are modeled basically into two groups, continuous and discrete. Discrete models include assignment to settlements and related topics. Continuous models are generally linear problems studying median problems.

In the literature, there are many solutions developed for problems about ambulance and fire department services. These studies have various areas like planning, facility location, communication, healthcare systems, and logistics. Consequently, the different facility location studies in the literature are Schilling et al. (1980) emergency service vehicle allocation, Batta et al. (1989) healthcare systems location, Hale and Moberg (2003) distribution systems, Fathali and Khaki (2006) transport networks, and Drezner and Suzuki (2009) covering continuous demand solutions towards healthcare system problem.

The first studies about fire station layout started with Plane and Hendrick (1974). They developed a mathematical model that meets the demand based on the projected time and distances of the previous studies of emergency service station locations by Toregas et al. (1971). The importance of this study is that it shows the solution of both the binary integer model and the linear model for the first time. Authors of this study also proposed a modified median model. Furthermore, median models are frequently observed in the studies next to the cluster coverage model.

In recent years, we came across studies of healthcare service location and related topics. Verter and LaPierre (2002) used probabilistic methods to try to determine preventive healthcare service locations. Studies like this were also made by Ndiaye and Alfares (2008), Kim and Kim (2010), and Zhange et al. (2010). During their studies, authors used branch and bound algorithm to solve the mathematical model problems of preventive healthcare service locations. In this study where the solution method's effectiveness was observed, they saw that when the number of variables in a model increase, it becomes harder to solve the model.

In the literature, it was observed that facility location problems are trying to optimize the distance to meet the demand and to minimize the response time. Hakimi (1983), Infante and Taborga (2001), Lorenna and Senne (2004), Choi and Lee (2007), Osman and Amadi (2007), Resende and Werneck (2007), Dominguez and Munoz (2007), and Bischoff and Dachert (2009) can all be counted as the studies that developed models that meet the demands at the minimum amount of time. Galveo et al. (2000), Hong et al. (2004), and ReVelle et al. (2008) made the studies about facility location where the main factor was meeting demands. Consequently, study about emergency healthcare service systems by Kim et al. (2012) suggested network models.

Another study area about fire station location involves an economic approach including budget evaluation processes. Badri et al. (1998) suggested a model for the fire station location problem using multi-target programming. During this study, authors used constraints that will minimize operating costs aside from the fixed costs. With these constraints, the change of the yearly operating costs and fixed costs at the projection range can be seen. Church et al. (2009) pointed out that the yearly repair and maintenance costs of fire stations are very high. In this study, personnel expenses also create high costs aside from installation and fixed costs. However, these studies showed that determining fire station location is very important both strategically and economically.

It is known that there are two types of solution methods for mixed integer programming, exact and heuristics or approximate. The former include cutting plane, branch and bound, branch and cut, Lagrange Relaxation, decomposition methods, and so on. The latter are heuristics and meta-heuristics. In addition, GA is the second category.

Murray (2013) in his study suggested a mathematical facility location model including approaches of planning for strategic targets and purposes. In the study, the solution is found with a mathematical model using the data received from the geographical information system (GIS). With this method (GIS), they suggested a new approach for determining urban location of fire stations.

Consequently, there are other studies in our country which determines the location of fire station. Thus, these studies generally make use of the mathematical modeling approaches. Çatay et al. (2008) solved single and multi-period planning problem of the units connected to İstanbul Metropolitan Municipality Fire Department. In the study, the authors suggested a mathematical model based on the cluster coverage model. Also, they suggested a heuristic solution method when the model becomes hard to solve.

During another study for the city of Istanbul where the target was for fire station locations to include all of the municipal borders, Aktaş et al. (2009) used the cluster coverage model. In this study, it was stated that the firefighter team's case intervention was limited to 5 minutes. In this study, the authors created a cluster coverage model that uses geographical information systems (GIS).

Proposed Model

For the problem, mathematical model was modeled by mixed integer method approach. There are many definitions on mixed integer programming. In one of the definitions, the term mixed integer programming refers to all the mathematical model's variable to be an integer. If some variables are binary and some of the variables are integer, the model would be a binary integer model. In this problem, the mathematical model can be formulated as mixed integer linear programming model. The model solution method changes according to the nature of the problem. If the model is NP-Hard, the solution method can be selected as heuristic. Furthermore, Genetic Algorithm (GA) is one of the best known heuristic algorithms. Genetic algorithm is preferred to the others, especially if the problem size is extremely large or the model variable is non-linear. In fact, genetic algorithms are probalistic domain search approach which is established on a nature evolution process. It is known as nature evolution process just as Darwinian approach. Therefore, this fits the best value or is a suitable offspring for model solution. There are many steps for Genetic Algorithm (GA). Firstly, is in determining the number of choromozomes, generation, and mutation rate, in addition to the crossover rate. Secondly, after determining the attributes, the values is initialized; and some processing choromozome selection, mutation, and new offspring generation is managed. Finally, is to select one of the best value which is the fulfilling object function.

In this problem, the current capacity and fire stations is taken into consideration in order to fulfill this model. Thus, we consider these assumption in the model: i) Each Region is served by one station, ii) Total number of facility is limited, iii) Distance and servicing region is not more than 25 minutes, because of prohibited law. Service region distance is limited by governmental procedure. Time should not be exceed given limits.

Therefore, the notations which variable, parameter, and indexes are using in the model are given under:

I: set of demand region

J: set of candidate region

i: demand index $\forall i \in I$

j: candidate index $\forall j \in J$

k: fire station type k=1,2,...,n

P_i: i. demand region call type k

d_{ij}: distance from i. demand to j. candidate region

c_{jk}: capacity of j. candidate region k type

Q_{ij} : (0,1) distance covering matrix from i demand to j., $Q_{ij=}$ $\{ d_{ij} \mid d_{ij} < 25 \}$

B: total budget

TS: total number of facility
F_{ik}: i demand region k type facility setup cost
Decision variables;

$$y_{ijk} = \begin{cases} 1\text{ , if candidate k. th type i. service from j. demand} \\ 0,\ \text{otherwise} \end{cases}$$

$$x_{jk} = \begin{cases} 1,\ \text{setup i. demand region} \\ 0,\ \text{otherwise} \end{cases}$$

Thus, the model of the problem was developed in the order given below:

$$Max\ Z = \sum_i \sum_j Q_{ij} P_i y_{ijk} \tag{1}$$

St.,

$$\sum_j \sum_k x_{jk} = TS \quad \forall\ \text{k} \in K \qquad \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{2}$$

$$\sum_j y_{ijk} = 1 \qquad \forall\ \text{i} \in I, \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{3}$$

$$\sum_j y_{ijk} \leq x_{jk} \qquad \forall\ \text{i} \in I, \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{4}$$

$$\sum_i P_i y_{ijk} = C_{jk} \qquad \forall\ \text{i} \in I, \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{5}$$

$$\sum_j f_{jk} x_{jk} \leq B \qquad \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{6}$$

$$x_{jk}, y_{ijk} \in \{0,1\} \qquad \forall\ \text{i} \in I, \forall\ j \in \text{J and } \forall\ \text{k} \in K \tag{7}$$

Formulation number (1) is the objective function. Thus, it covers the maximum population at minimum distance. Formulation (2) shows that total facility can be opened. Formula (3) gives us at least one demand region that needs services from one facility. Constrained (4) service provides only opened station. Covering population (5) is hard constrained and also fulfills the demand. Budget constraint (6) states that it should not exceed the amount of total budget. Integrality constraint (7) enforces yes or no if stations location sets up or the service provides.

Solution Method

Many project or academic paper is surveyed by binary GA in literature. As mentioned earlier, Genetic Algorithm (GA) consists of four main stages: evaluation, selection, crossover and mutation, respectively. Each procedure is iterative and has its own attributes. In the iterative process, GA continues working till the best or suitable value is met. As we saw in the model, there are two types of variable. One of them is binary, while the other is integer. Consequently, we have chosen solution method Binary GA in the case of including binary variable. Considering this model, Binary decision variable is chosen as choromozomes for binary GA. Generally, genetic algorithm uses non-linear programming models. Thus, binary genetic algorithm mostly uses linear or binary and mixed integer programming models. In addition, MS Office and Visual Basic computer programming language were used in solving the mathematical model.

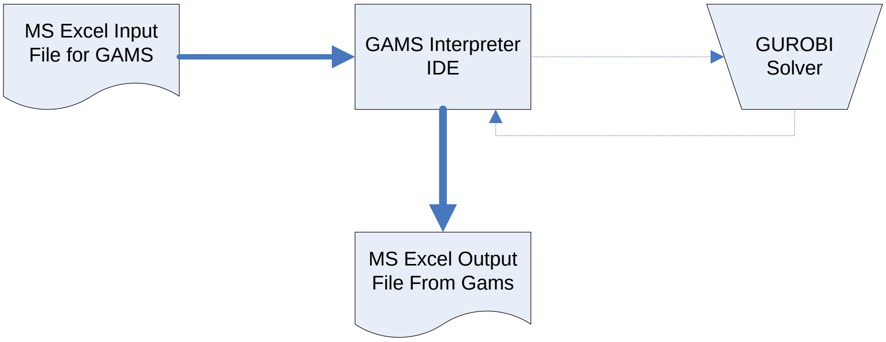

Figure 1. GAMS Data Input/Output Flowchart

Numerical solution was obtained by GAMS (General Algebric Modeling System). Location, parameter, and the other data were sent using computer programming which was developed before. Computer program is divided into two main parts. One part is MS Excel which sends input data, and the other part collects the data from the environment. In order to solve the development of mathematical model, GAMS IDE was selected. Also, solver was GUROBI academic.

Developed mathematical model was coded GAMS IDE using binary GA method. Coding problem under GAMS and Binary GA, was modified and known as GA. Modified GA has resemblance to classic GA, except for decision variable in this survey.

Binary Genetic Algorithm

It is known that GA is one of the most heuristic optimization solution methods in NP-Hard problem. GA is an evolution based solution algorithm which is Darwinian approach. According to a survey, Yesugev and Karakaya (2014) mentioned that the solution method known as “Evolution Strategies” was firstly used by Rechenberg in order to optimize real values in the end of the 1960 (Rechenberg, 1973). During the research period, Fogel, Owens and Walsh (1966) also developed the concept of “Evolutionary Programming”. Furthermore, Holland and his students in Michigan University further developed GA from 1960 till the end of late 1970. After then, his published book was name as “Adaptation Natural and Artificial Systems” which was also referred to as genetic algorithm (GA) (Yesugev and Karakaya, 2014).

In this problem, we conform some of the parameter as follows: population, choromozomes, and offspring. In this solution, set formed by a cluster of problems is also possible to obtain the solution. Thus, this is regarded as population. The population, choromozomes, and offspring are taken shaped by vector which comprises the nature of the problem. The gene includes many numbers of array that consists of 0-1. Binary GA is similar to normal GA. Binary GA was selected in this problem for the aim of smoothly coding and getting the exact result.

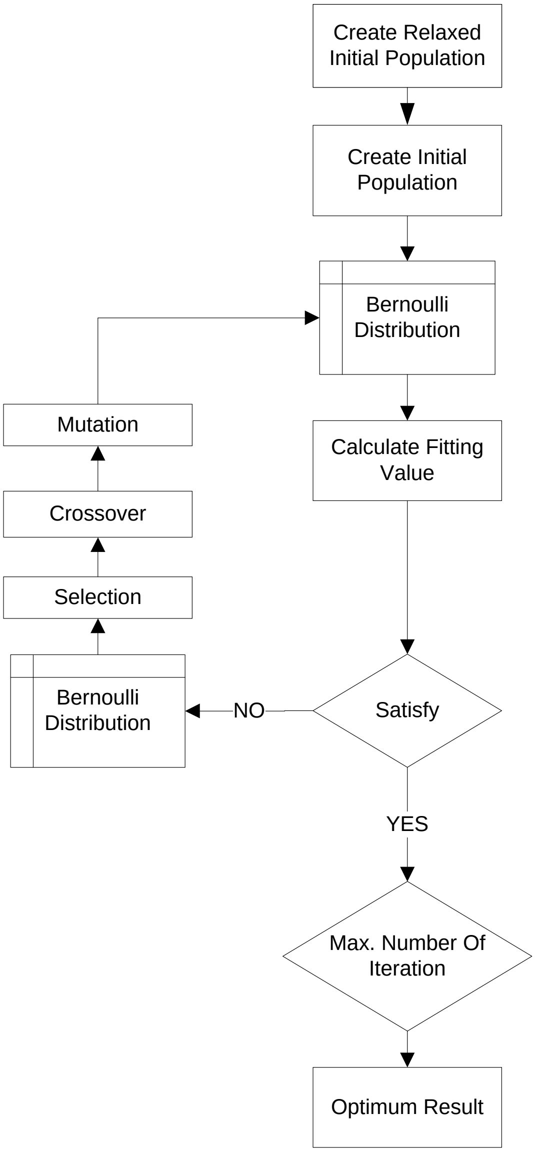

Figure 2. Modified Binary GA Apply to the Problem

Modified GA, which is binary GA flowchart is examined in Figure 2 in details. Binary GA was tailored in accordance with the original problem. Decision variables are binary integer number in binary GA. These decision variables are choromozomes. Therefore, when they are occurring in the initial population, their values are adjusted by Bernoulli (0,1) distribution. Algorithm continues to compare chromozomes till the result of the model is satisfied. Mutation rate is significant to obtain the expected object function value. Developed model as a binary GA; object function marginal value audits in respect of mutation rate; and iteration is follow-through if decomposition is present. If marginal value of the object function is close to zero or decomposition value, optimization which is the best value is obtain for the objective function.

There are many stages in Coding with binary GA. They include: to create initial population, to calculate fitting value, to apply crossover for genes, to apply mutation process, to create offspring, and finally to end the process. Also, we considered this a problem: sequencing of the problem and creating fitting values arranged emergency calling distribution in Samsun municipal. Initial population is the number of sum value which is been calling for emergency. Initial of value decision variables is used in the candidate region, y_{ijk}. The other is setup decision x_{jk}, which is given by Bernoulli distribution. The Bernoulli distribution has set of S= {(x,y) | (x,y) \ 0,1} and they are uniform independent variables. Two independent choromozomes also generated this problem. Also, each choromozomes belongs to only one decision variables whose initial value is related to set of **S**.

General GA pseudo codes are as follows:

1. Chose initial random population of individuals
2. Evaluate the fitness of individuals
3. Repeat {

Select the best individuals to be used by genetic operators
Generate new individuals using crossover and mutation
Evaluate the fitness of new individuals
Replace the worst individuals of the population by the best new individuals
}

4. Until stop criteria

Developed pseudo codes for modified Binary GA are as follows step by step:

1. To create initial integer model as relaxed
2. Repeat until the best value is gotten

Modified Binary GA {
To create initial population,
To determine the criteria for solution region,
To setup choromozomes Bernoulli uniform (0,1),

Do { send choromozomes to mix pool
Apply to choromozomes crossover operator
If choromozomes fit the object function, then
{ Apply to choromozomes change operator
Apply to each choromozome Bernoulli uniform (0,1) distribution according to fitting value
Create new population from previous population
} while (!(is iteration end) or ! (is stop fitting in choromozomes))
Select the best choromozomes as a result}
Else
Change the choromozomes and then continue solution procedure}

Preparing the Survey Data

As mentioned earlier, the data used in this study are arranged in the average of emergency calls during a year in Samsun municipal. Therefore, these data was shaped from MS Excel spreadsheet programs to GAMS. Covering zero to one matrix, Q_{ij}, is limited to a distance of 10 km. Also, it has a time limit of 25 minutes. As earlier mentioned, an excess of those limitations are ignored. Thus, covering matrix formula is represent as $Q_{ij} = \{ d_{ij} \mid d_{ij} < 25 \}$.

Table 1. Region Covering Matrix, Q_{ij}

AdayTalep	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16	j17
i1	0	1	0	1	0	1	0	1	0	0	1	0	0	0	0	0	0
i2	1	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0
i3	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
i4	1	0	0	0	0	1	1	1	0	0	0	1	0	1	0	0	0
i5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
i6	1	1	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0
i7	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
i8	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
i9	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
i10	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
i11	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
i12	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
i13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
i14	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0
i15	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
i16	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
i17	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Two genes were constructed because there were two decision variables in the model. The first gene belong to x_{jk} , while the second gene belongs to y_{ijk} decision variable. Table 1 shows covering matrix Q_{ij}, whether it covers from candidate or do not.

Table 2. Parameter Value of Binary GA

Binary GA Z_2 Parameters	Z_2 Parameters Value
Decision Variables	2
Average Number of Population	~936
Number of Iteration	1000
Mutation Rate	0.01
Crossover Rate	0.01
Fitness Function	0.01

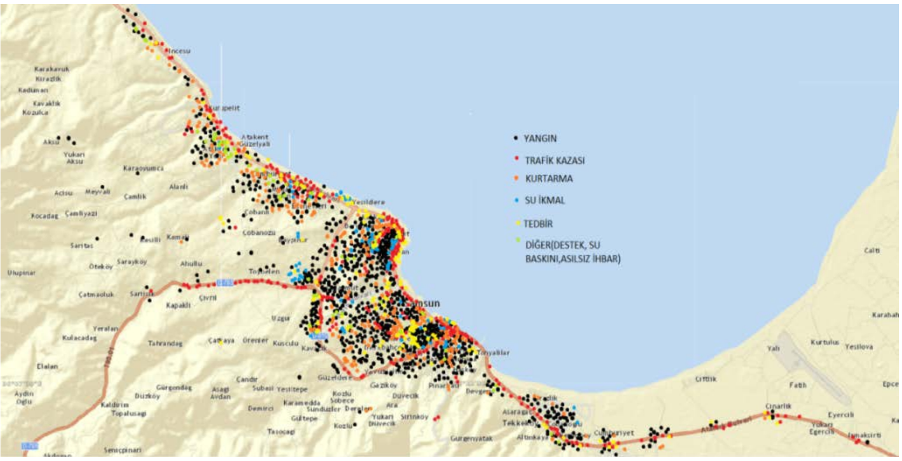

Figure 3. According to Call Type Samsun Municipal Map

The image on the map in Figure 3 shows the emergency call to the fire department for a year in Samsun municipal. According to the map, emergency calls spreads in Samsun municipal area from more dense city center to sparse rural area.

The Survey Conclusion

The model runs after it was developed. Thus, their results were acquired from coding GAMS model. The coding GAMS model runs on intel i7 2.7 GHz processor on a 16 GB RAM computer. However, no other program could be run on it. The exact result whereby the program code runs 1000 iteration was obtained at the end of 113 minutes. First inception result objective Z_1 function was obtained when it was relaxated. The results from initial value was used as an input to Z_2 objective function which was a modified binary GA. Aftermath, a number of 10 stations according to their types was seen on Table 2. In this survey, one scenario tries to solve problems under non-rush hours. All station was established north of the highway line. Subsequently, it should be noted that fire station is more close to highways for easy connectivity.

Table 3. Solution Fire Station Location according to Types

Candidate Region	**Fire Types**		
	k1	k2	k3
j1		1	1
j3		1	
j4	1	1	1
j5	1	1	
j6	1		
j7	1		

The opening of fire station in candidate region with respect to their types are k=1 number of 4, k=2 number of 4, and k=3 number of 2. Considering Figure 3, k=1, as a red color legand, seems to appear in more dense city center. Fire station type k=1, is red color legand, which appears adjacent to the other same type. Thus, there are many reasons for this instance. For one of them, the region has more intense population than the other regions. The other reason for this situation is to fulfill the demand from the candidate point. One of the station, x_{jk}, i.e., k=1, is a long way off the others in order to collect far away local P_i demand.

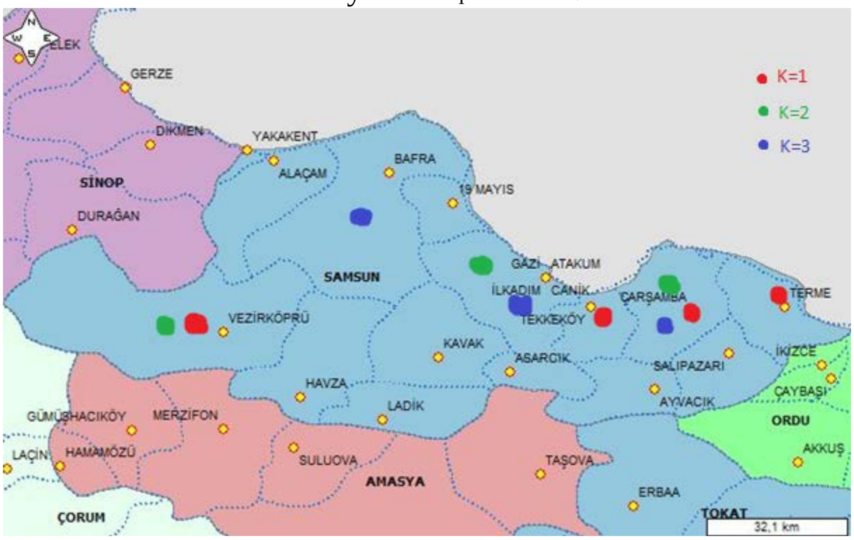

Figure 4. Fire Stations Location according to Types

Furthermore, when it is far from the population intense location, fire station is less dispersal in the region. For instance, fire station type k=2 and k=3 is located far away from the others. This case shows us that the results are related to factual situation. Examining the numerical results in Figure 5, we can see that known GA objective function best value is Z_2= 74.89, and the modified binary GA best Z_2 value is Z_2= 78.83.

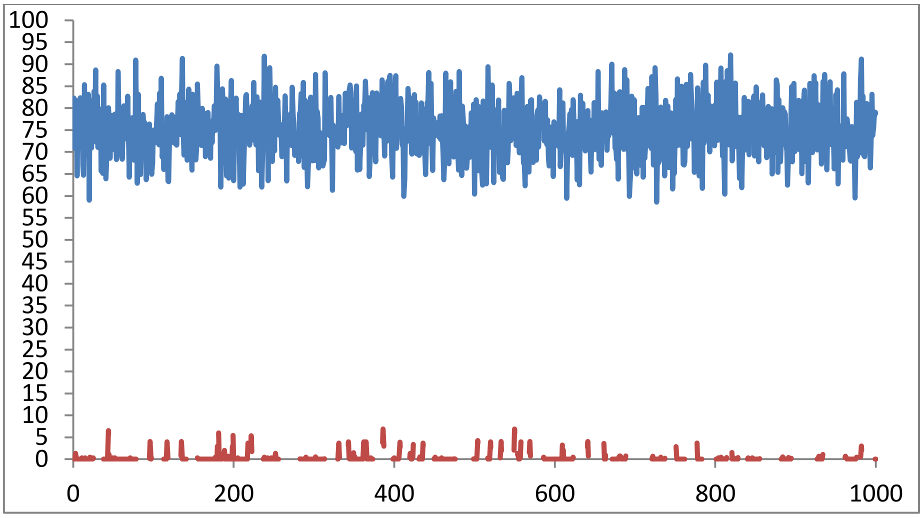

Figure 5. 1000 Iterations Objective Function Results

As we can see from Figure 5, results were periodically dispersed from 65 to 85. Also, line color is blue and deviation from average objective value color is red. Also in Figure 6, we can see that there are 180 points deviation from known GA objective function average value. In addition, we can interfere that binary GA at some solution is more tightly than GA. Iteration of the binary GA average values acquired Iter=74.89, and standard deviation □ is 6.069. Average values between binary GA and known GA, and $\bar{\Delta}$= 1.32 standard deviation of these values is 1.66. Therefore, the values results obtained ensure fitting function value of the binary GA owing to the less fitness function value of the original problem.

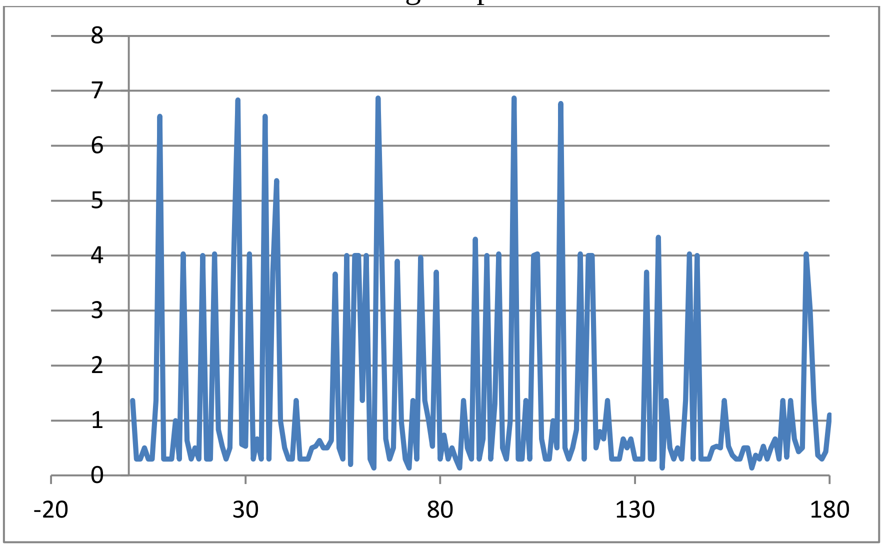

Figure 6. Deviation Graph between Known GA and Modified Binary GA

Consequently, we can conclude that the binary GA can give us the best value at 180 point. Known GA gave the worst value at 6 point that deviation (□) value is approximately Z_{max}□=7 in Figure 6. With respect to Figure 6, average point is $\bar{Z}_{max}$□□□□□□□□ deviation value. And then, deviation rate peak level seems to be at 6 different point at %10 percent. In addition, the other 152 points are deviate %1 and %5 percent. According to this observation, binary GA gave us the best objective value than classic known GA. Statistical report of Deviation Graph is represented in Table 4.

Table 4. Statistical Report of Deviation Graph

	Valid N	**Mean**	**Sum**	**Min**	**Max**	**Var.**	**Std.Dev.**	**Std. Error**
Var1	180	1.323333	238.2000	0.133	6.866	2.787038	1.669442	0.124433

The problem to be solved in this survey gives us a new approach to fire department station location problem. However, the results were compared with classic known GA and binary modified GA. Binary GA delivers up the best value for this problem. Thus, future works for this problem should consider stochastic constrainted. Thus, it is known chance constrained programming.

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