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Simulation Modeling of Fire Station Locations under Traffic Obstacles

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***Abstract*—**Facility location problem involves locating a facility to optimize some performance measures. Location of a public facility to serve the community, such as a fire station, significantly affects its service quality. Main objective in locating a fire station is to minimize the response time, which is the time duration between receiving a call and reaching the place of incident. In metropolitan areas, fire vehicles need to cross highways and other traffic obstacles through some obstacle-overcoming points which delay the response time. In this paper, fire station location problem is analyzed. Simulation models are developed for the location problems which involve obstacles. Particular case problems are analyzed and the results are presented.

***Keywords*—**Public Facility Location, Fire Stations, Response Time, Fire Vehicle Delays.

I. INTRODUCTION

THE Facility Location Problem (FLP) involves locating facilities to optimize some performance criteria. The problem occurs in practical applications related to locating industrial facilities, such as manufacturing plants, and service facilities, such as bus-stops, fire stations, hospitals, etc. Facility location problems have been the subject of analysis for centuries and have received considerable attention over the years. Effective location of emergency services within geographical areas is an important problem. In particular, location of a fire station has a significant effect on its operational capability and performance. Since a fire station supports the needs of the fire department and the community in which it is located, location of a station is largely driven by the need to minimize response time, which is the duration between receiving a call and reaching the place of incident.

The decision of where to locate a fire station depends upon a set of tangible and intangible criteria that are unique to a given problem. Most of the models developed are either limited due to their capability in solving large scale problems or specific for selected problems. Most of the traditional models incorporate only travel times or travel distances, which may not be enough to achieve best performance. Other criteria, such as population density must also be incorporated into the models. Several research papers have appeared in the literature on the fire station location analysis. Various mathematical and heuristic models have been developed for location analysis of fire stations [1]-[4]. Procedures have been developed for optimal siting of fire stations using GIS and ANT algorithm [5]. Also fuzzy multi-objective programming models are utilized for the optimization of fire station locations through genetic algorithms [6]. Interaction of analytic hierarchy process (AHP) and geographic information systems (GIS) in multi-criteria site selection problem for fire services have been discussed in the literature [7]. A review of current research on fire station locations can be seen in [8].

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In this paper, a model is developed to determine the optimum location for a new fire station which is planned to serve two areas separated by an obstacle in a city. An obstacle is usually a highway that can be crossed through an obstacle-overcoming point, which may be a major overpass, an underpass, or any other traffic junction with traffic lights. An achievement function is developed based on the distance from the fire station to the fire areas and the population density in each individual fire area. Location of a fire station determines its distance to all possible fire areas served and the distance affects the response time. Complete fire areas are divided into grids and the population density in each grid area is utilized to determine the expected number of fire incidents based on the relation between the number of fire incidents and the population density.

II. FACTORS AFFECTING FIRE STATION PERFORMANCE IN METROPOLITAN AREAS

One of the most important criteria in locating a fire station is the response time (RT), which has various definitions. In a fire service, total RT is measured from the time a call is received by emergency center to the arrival of the first apparatus to the incident point. For the public, the clock for RT begins when the public becomes aware that there is an emergency incident and the fire department is notified. In reality, however, the RT for fire suppression may begin at the moment of fire ignition and continues until the fire is extinguished. RT exceeding 5 minutes can be serious in many situations because fire in some areas can easily spread and threaten lives. Therefore, it is desired to have the RT<5 minutes if possible. Many factors, as categorized below, may affect the response time.

1. The traffic situation: It may be affected by the layout and location of the fire station, the population density in the area and the rush hours.
2. Size of the area covered and the station location.
3. Type of area: Industrial, commercial, or oil fields.
4. Number of incidents, which depends on the population size in the area and fire station capacity.

In order to reduce the RT, it is necessary to consider the issues above. In addition to RT, number of incidents per year in each area is also an important factor in formulating an objective function to optimize fire station location. As a case example, number of incidents per year and population data was obtained for 29 fire areas in the State of Kuwait. The number of incidents was plotted as a function of the population. Fig. 1 shows the relation between the number of incidents and the population in 29 areas in the city. A linear regression equation given below was developed using MINITAB statistical package.

$$Y = 146 + 0.0042\,X \qquad (1)$$

Where Y = Number of incidents in an area and
X = Population of the area.

Correlation coefficient of R^2=86.3% indicated a reasonable relationship between X and Y. Expected number of incidents at each point in the city is a function of the population at that point and the ability to reach that point depends on the distance from the fire station.

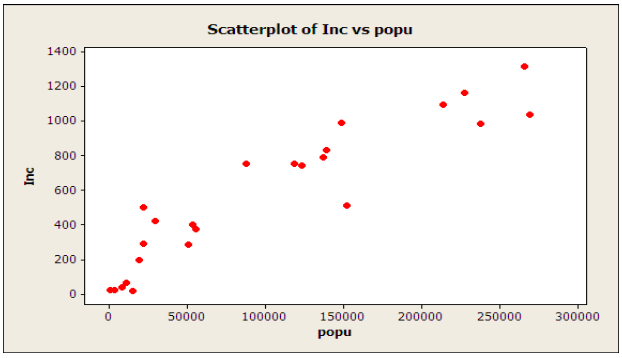

Fig. 1 Number of incidents vs. population size

III. Optimal Location of Fire Stations with Obstacle-Overcoming Points

One of the problems in locating a fire station to serve some regions is the consideration of obstacles. Obstacles are highways that divide the areas while obstacle-overcoming points are intersections, such as bridges and traffic junction points that block and delay transportation between the areas. A fire station should be located in a point in the area such that the response time to all the points in all areas covered is minimized and maximum population (or number of incidents) are reached with minimum time under obstacle-overcoming points restrictions. In this section, a fire station location model is developed based on a case in Kuwait. A residential area, shown as Planning Area 1 in Fig. 2, is relatively new with rapidly increasing population in Kuwait. Numbers of fire incidents are also increasing with increasing population and the residential buildings. A fire station is being planned to serve this area. However, the planned new fire station for this area is supposed to serve a neighboring area, shown as Planning Area 2 in Fig. 2. Each one of these planning areas is considered as a sub-area and the new fire station will serve both areas, which are divided by a major highway, considered as an obstacle, and an obstacle-overcoming point which is a bridge with a traffic light. The location of the fire station should be selected in such a way as to overcome the obstacle through the obstacle-overcoming point and arrive to the incident place with minimum response time and maximum population coverage. The demand for firefighting from all points in both areas must be met. Each area will be divided into smaller grids for analysis. In order to solve the fire station location problem a model is developed based on a function called Achievability Strength. The following notations and variables are introduced with respect to Fig. 2.

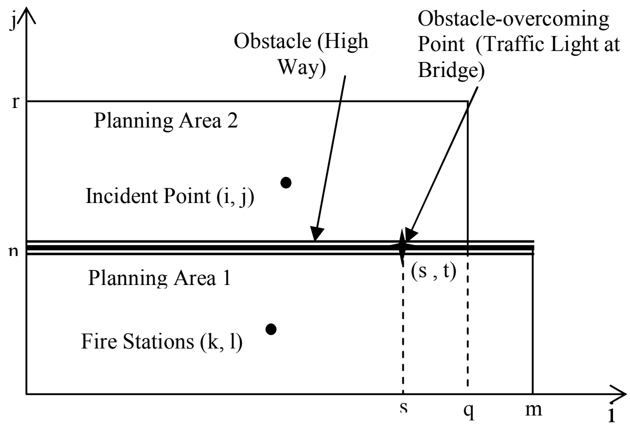

Fig. 2 New fire station in two areas with an obstacle and an obstacle-overcoming point

m, n= Coordinate points of the borders of Planning Area 1 (m= 6000 meters; n=4000 meters)
q, r = Coordinate points of the border of Planning Area 2 (q= 5000 meters; r=7000 meters).
k, l = Coordinate points of new fire station.
s,t = Coordinate points of the obstacle-overcoming point (s= 3000 meters; t= 4000 meters).
i, j = Coordinates of the grid of incident place.
P_a = Population of the area a; a=1, 2.
G_a = Number of grids in the area a; a=1, 2.
Y_{aij} = Estimated number of emergency incidents in area a and grid (i, j) as a function of population.
h_i = Maximum Euclidean distance from the fire station located at point (k, l) in planning area i to the farthest point in all areas covered by the fire station.
From previous analysis in section 2, Y_{aij} is determined as: $Y_{aij} = (146 + 0.0042\,P_a)/G_a$

(2)

Value of h_i can be calculated based on the following formulas, which are based on the Euclidean distance from the fire station to the farthest corner points in both planning areas. It takes into account the location of the fire station with respect to planning areas. If the fire station is located in planning area 1, Euclidean distance from (k, l) to upper right corner of area 1, lower right corner of area 1, upper left corner of area 1, lower left corner of area 1, upper right corner of area 2, and upper left corner if area 2 are given in the order below.

$D_{11}=\sqrt{(m-k)^2+(n-l)^2}$; $D_{21}=\sqrt{(m-k)^2+l^2}$

$D_{31}=\sqrt{k^2+(n-l)^2}$; $D_{41}=\sqrt{k^2+l^2}$

$D_{51}=\sqrt{(s-k)^2+(t-l)^2}+\sqrt{(q-s)^2+(r-t)^2}$

$D_{61}=\sqrt{(s-k)^2+(t-l)^2}+\sqrt{s^2+(r-t)^2}$

Lower corners of area 2 are not considered since the distance will be smaller than upper corners.

h_1 is found as: h_1= Maximum (D_{11},.., D61) (3)

A function, called "Relative Achievability Strength", is defined with respect to fire station location, fire incident location and the total coverage area. The function takes a value between 0 and 1. Its value depends on the point where the fire station is located. Thus, there are two possibilities:

1. If the fire station is located in area 1 and the incident is in area 1, the following definitions apply:

g_1= Euclidean distance travelled from the fire station located at point (k, l) in planning area 1 to the fire incident at point (i, j) in planning area 1.

F(i,j,k,l,h) = Relative Achievability Strength of the fire vehicle to reach the fire incident place at (i, j) in planning area 1 when the fire station is located at point (k, l) in planning area 1.

$$g_1=\sqrt{\left[(k-i)^2+(1-j)^2\right]} \tag{4}$$

$$F(i,j,k,l,h_1) = 1-g_1/h_1 \quad \text{if } g_1 < h_1 \\ = 0 \text{ otherwise} \tag{5}$$

Note that F(i,j,k,l,h)=0 if $g_1=h_1$ and F(i,j,k,l,h)=1 if g_1=0. It means that this function is 0 for the farthest point in the covered areas and 1 for the point next to the fire station.

2. If fire station is located in area 1 and the incident occurs in area 2, the following definitions apply:

g_2 = Euclidean distance travelled from the fire station located at point (k, l) in planning area 1 to the fire incident at point (i, j) in planning area 2.

g_{21}= Euclidean distance from the fire station at (k, l) to the obstacle-overcoming point at (s, t).

g_{22}= Euclidean distance from the obstacle-overcoming point at (s, t) to incident place at (i, j). F(i,j,k,l,s,t,h) = Relative Achievability Strength of the fire vehicle to reach the fire incident place at (i, j) in planning area 2 with the obstacle-overcoming point at (s, t) when the fire station is located at point (k, l) in planning area 1.

Total distance travelled in Euclidean measure with obstacle-overcoming point at (s, t) is as below.

$$g_{21}=\sqrt{\left[(k-s)^2+(1-t)^2\right]} \tag{6}$$

$$g_{22}=\sqrt{\left[(s-i)^2+(t-j)^2\right]} \tag{7}$$

Thus, $g_2 = g_{21} + g_2$ (8)

$$F(i,j,k,l,s,t,h) = 1-g_2/h_1 \quad \text{if } g_2 < h_1 \\ = 0 \text{ otherwise} \tag{9}$$

Note that relative achievability strength, F=0 if travel distance g_2=h_1, that is the distance fire vehicle travels is equal to the maximum possible distance that it needs to travel within the coverage area as mentioned for the case above. Effectively, achievability strength is zero for the farthest point. Similarly, achievability strength F=1, if the distance fire vehicle travel is zero (g_2=0), which means that the incident is next to the fire station. All other values are within these two extremes for all incidents. Next we consider the case when the fire station is located in area 2 and the incidents are either in area 1 or in area 2. The maximum distance needed to travel to cover all areas, h_2, is calculated similarly as below. Euclidean distance from (k, l) to upper right corner of area 2, lower right corner of area 2, upper left corner of area 2, lower left corner of area 2, lower right corner of area 1, and lower left corner of area 1 are given in the order below:

$D_{12}=\sqrt{(q-k)^2+(r-l)^2}$;

$D_{22}=\sqrt{(q-k)^2+(l-n)^2}$.

$D_{32}=\sqrt{k^2+(r-l)^2}$; $D_{42}=\sqrt{k^2+(l-n)^2}$

$D_{52}=\sqrt{(s-k)^2+(t-l)^2}+\sqrt{(m-s)^2+t^2}$

$D_{62}=\sqrt{(s-k)^2+(t-l)^2}+\sqrt{s^2+t^2}$

Upper corners of area 1 are not considered since the distance will be smaller than lower corners. Value of maximum distance, h_2, from the fire station is found by: h_2= Maximum (D_{12},…,D62) (10)

Relative Achievability Strength is similarly defined with respect to the location of the fire station, location of the fire incident and the total coverage area. The function takes a value between 0 and 1. Its value again depends on the area where fire station is located. Thus, there are two possibilities: If the fire station is located in area 2 and the incident occurs in area 1 or area 2, the following formulas apply:

g_1 = Euclidean distance travelled from the fire station located at point (k, l) in planning area 2 to the fire incident at point (i, j) in planning area 1. Since there is an obstacle overcoming point, this distance has two components as before.

g_{11} = Euclidean distance from the fire station at (k,l) to the obstacle-overcoming point at (s, t).

g_{12} = Euclidean distance from the obstacle-overcoming point at (s, t) to incident place at (i, j). g_2 = Euclidean distance travelled from the fire station located at point (k, l) in planning area 2 to the fire incident at point (i, j) in planning area 2.

F(i,j,k,l,s,t,h) = Relative Achievability Strength of the fire vehicle in planning area 2 to reach the fire incident place at (i, j) in planning area 1 with an obstacle-overcoming point at (s, t).

F(i,j,k,l,h) = Relative Achievability Strength of the fire vehicle to the fire incident place at (i,j) in planning area 1 when the fire station is located at point (k,l) in planning area 2.

$$g_{11} = \sqrt{\left[(k-s)^2 + (1-t)^2\right]} \quad (11)$$

$$g_{12} = \sqrt{\left[(s-i)^2 + (t-j)^2\right]} \quad (12)$$

Thus, $g_l = g_{11} + g_{12}$ (13)

$F(i,j,k,l,s,t,h) = 1 - g_l/h_l$ if $g_l < h_l$ (14)
= 0 otherwise

$$g_2 = \sqrt{\left[(k-i)^2 + (1-j)^2\right]} \quad (15)$$

F(i,j,k,l,h) is defined as follows:

$F(i,j,k,l,h_l) = 1 - g_2/h_2$ if $g_l < h_l$ (16)
= 0 otherwise

F(i,j,k,l,h)=0 if $g_2=h_2$ and F(i,j,k,l,h)=1 if $g_2=0$.

Finally, an equation which combines achievability strength and the expected number of incidents for each grid point is established as a performance measure for evaluation of all possible fire station location points. Note that the number of incidents depends on the population size as established with regression equation (1) and (2) above. Achievability strength F depends on h and the travel distance g (which in turn depends on i, j, k, l, s, and t) within the coverage area and calculated as given above. This function is multiplied by the expected number of incidents in each grid and integrated over all grids for each possible fire station location. Thus, D_l= Fire Fighting Ability for any point (i, j) in the Planning Area 1, assuming that the fire station is located at any point (k, l), is given by the equation:

$D_l = Y_{aij}F(i,j,k,l,s,t,h)$ (17)

This formula implies that the ability to reach and serve the demand for fire service at a point is not only determined by the distance factor incorporated as the achievability strength, but by the product of the expected number of incidents, which is a function of the population density in each area, and the achievability strength at that point. Thus, D_l for each point depends on the location of the point itself, the location of the fire station, and the number of incidents which in turn depends on population at that point. A similar measure is determined for the points in area 2 by D_2 as follows:

$D_2 = Y_{aij}F(i,j,k,l,s,t,h)$ (18)

Overall Fire Fighting Ability, D, to serve all demand points in both areas is calculated by integrating both functions above over all grids in both areas for both regions and adding them up as follows:

$$D = \int_0^n \int_0^m D_1 d_i d_j + \int_n^r \int_0^q D_2 d_i d_j \quad (19)$$

Where, d_i and d_j represent derivation in the x and y direction. Optimal location of the fire station is obtained by maximizing D, or by determining D_{max} for the maximum Total Fire Fighting Ability.

IV. Application of the Model

The integration problem given by equation (19) is difficult to solve analytically. In order to apply the above model, integration was solved by discrete simulation. In order to incorporate the number of incidents into the location model as a function of population at each point, the total area was divided into grids of 50x50m =2500 m^2 and the number of incidents was estimated by equation (2) for each grid. For the particular problem, population of area 1 was P_1=40,000 and population of area 2 was P_2=25,000. Numbers of grids are calculated from the dimension of the areas. Referring back to fig. 2, m=6000, n=4000, q=5000, r=7000, while each grid is 50x50 m. Thus, area 1 has G_1=9600 grids and area 2 has G_2=6000 grids. Thus, using equation 2, expected number of incidents in area 1 is Y_{1ij}=0.03271 and the expected number of incidents in area 2 is Y_{2ij}=0.04183. A simulation program was developed to evaluate the integration given by equation (19) by discrete summation of the values for each grid. For the case problem considered, a total of 15,600 possible fire station locations (k, l) are evaluated by calculating the integration over all grids. For each of 15,600 fire station location point, summation is performed over 15,600 possible incident points in both areas. Therefore, a total of 15,600x15,600= 243,360,000 possible distance measures are evaluated and summed to reach a final optimum with respect to the performance measure.

Because a large number of possibilities need to be evaluated, a program was developed based on Visual Basic Software and the model was implemented through an interactive program. When the executable program is run, the first interactive screen as shown in fig. 3 appears. The user enters the parameters related to the fire areas in which a fire station will be located. As it is seen from fig. 3, the user enters coordinate points of the borders of areas considered (m, n, q, r) and the coordinate points of obstacle point (s, t). The user also enters population of each area and the grid size. As the grid size is reduced, number of possibilities and the simulation run time are increased. The input data on the screen can be cleared by the "clear" button and reinstated to the previous inputs by the "previous inputs" button. "Exit" button is used to end the program. "Run" button causes the program to run. The "Station Point" and "Incident Point" shows the simulated points as they are changed and the results evaluated. Selecting the "Grid View" would show the results for each individual grid. "Fire Stations" button would produce the results for all possible fire station locations in all grids as shown in fig. 4. This display shows all possible fire station locations (k, l), the achievement function (FA), and the maximum distance from the fire station to the incident places. These values are displayed in sequential manner according to the simulation. At the bottom of the display, the optimum fire station location, the optimum value of achievement function, and the maximum h value (denoted as H in the output) are also shown. If "Optimum Value" button is selected in the initial display screen, only optimum location, as shown in Fig. 5, is displayed without other values for all grids.

Execution time for the simulation program depends on the size of the areas covered and the grid size selected. For the case example presented above, 243,360,000 possibilities are simulated, which takes about 3 minutes on a typical PC with Intel Centrino Processor. The same simulation program was written in FORTRAN language to test the execution time. The execution time with FORTRAN was 1 minute on the same computer. Visual Basic was preferred for this application because of better interactive screen possibilities.

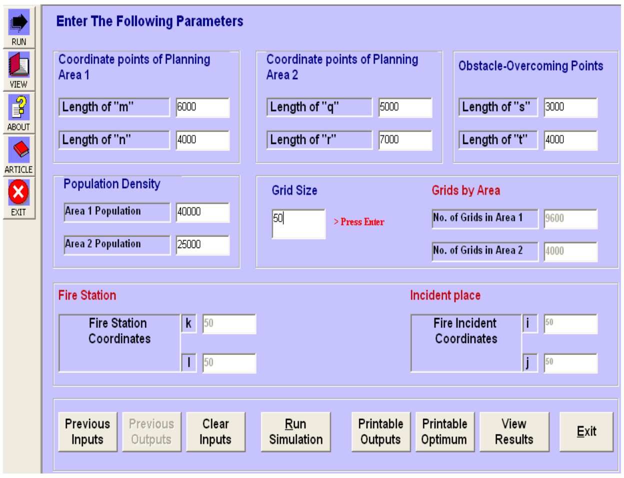

Fig. 3 First interactive page for entering parameters for fire areas considered

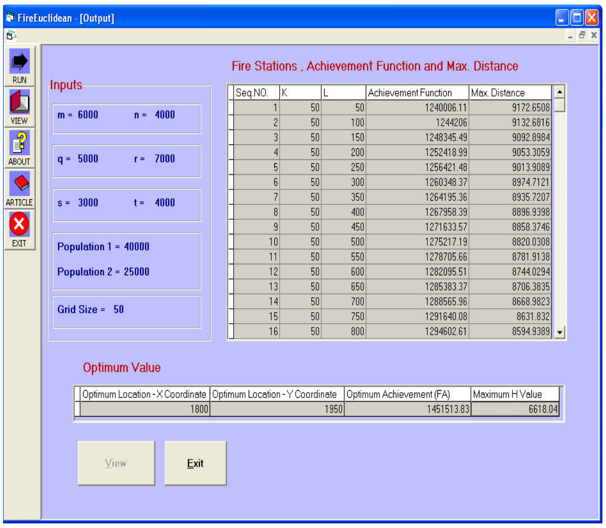

Fig. 4 Simulated values k, l, FA, and H in sequence and optimum location

V. Conclusion

Locating a fire station in an optimum point with respect to incident points is very important for fire fighting ability of the fire station. The level of service given to the community is significantly affected by the location decision. The simulation model developed in this paper can be used to locate a fire station under obstacle-crossing constraints. Obstacles separate two areas served by the same fire station. Because number of fire incidents is a function of population size, an achievement function is developed by incorporating the distance factor and possible number of incidents in each individual grids. Distance factor is necessary to consider in the location model since it directly affects the response time. The number of incidents in each grid area is also included in the objective, or the achievement, function in order to give proximity preference for the areas with higher number of incidents.

The model is used to solve the location problem and the optimum location point is determined for a fire station in Kuwait. The results indicate that the model can be useful in solving similar location problems. Furthermore, the same procedure can be utilized to incorporate other performance measures in evaluating possible locations and determining the optimum point. Future analysis could be carried out in relation to stochastic number of incidents at each point instead of deterministic values. Such analysis would require determination of statistical distributions that describe the number of fire incidents in the areas of concern. Simulation could be utilized in solving such problems. Other future extensions could include more than two areas with more than one obstacle overcoming point that link these areas. Similar analysis can be carried out with additional formulations.

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