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Abstract

An extension to models for the Maximal Covering Location Problem (MCLP) is applied to the Saudi Arabian Red Crescent Society (SARCS), Riyadh City, Saudi Arabia. The purpose is to identify the optimal locations of emergency medical service (EMS) stations. This is achieved by firstly locating these stations so the maximum expected demand may be reached within a pre-specified target time. Then, secondly, ensuring that any demand located within the target time will find at least one ambulance available. The demand rates are identified when it is necessary to add an ambulance in order to maintain the performance level for the availability of ambulances.

Keywords: health, location

Introduction

Health services are among the most important services that are required for developing nations. Saudi Arabia, as one developing country, attempts to provide the necessary health services for its people. The aim of the emergency medical service (EMS) of Saudi Arabia is to reduce the mortality and health deterioration caused by emergency incidents or illness in general. This requires suitable care to always arrive on time to the patients where required. Therefore, rapid response to an incident is one important measurement of the EMS system success.

However, the EMS is provided within a tight public sector budget that means the resources available to the EMS are limited. Therefore, a rational and optimal way of locating EMS stations and allocating EMS ambulances to these stations is required.

A model has been developed and applied to the EMS of Riyadh. The model seeks to locate stations and allocate ambulances to help the goals of the EMS authority to be achieved. This model seeks to maximise the probability of arriving at the sites of incidents within a target time. However, two important aspects need to be allowed for, to ensure that the ambulance arrives to the patient within the target time. First, an ambulance should be available at the time of the incident, and second, the time it takes the ambulance to arrive to the patient at the scene should be controlled. Both these aspects are used within a goal programming formulation, which has been described more fully by Alsalloum and Rand[1], to find the optimal locations and allocations of the limited resources of the EMS.

Riyadh, Saudi Arabia

Saudi Arabia lies at the furthermost part of Southwest Asia. It is bordered to the North by Kuwait, Iraq and Jordan, to the West by the Red Sea, to the East by the Arabian Gulf, United Arab Emirates and Qatar, and to the South by Yemen and Oman. Saudi Arabia occupies about four-fifths of the Arab Peninsula, with a total area of over 2,250,000 square kilometres. The population of Saudi Arabia is more than 20 million.

Saudi has been one of the richest countries during the last two decades in the Middle East. However, after being involved indirectly in the Iran-Iraq war and then the Gulf War, the economy of Saudi has declined. The Saudi government paid a very large share to finance the two wars. In addition, oil prices declined sharply after these wars. As a result, the Saudi government moved from an overspending era to a new thrifty era.

Riyadh is the capital of Saudi Arabia, consisting of seventeen municipalities; Addeerah, Alnaseem, Oraija, Manfooha, Alolya, Arroudah, Almalaz, Albat'ha, Itaigah, Alshamal, Aljanoob, Mather, Assily, Di'riah, Irgah, Alhair, and Diplomatic. All these municipalities consist of quarters (see Figure 1). The population of Riyadh is more than 3.5 million. It covers an area of 40 kilometres in width by 55 kilometres in length.

Saudi Arabian Red Crescent Society

The Saudi Arabian Red Crescent Society (SARCS) was founded in 1983, and later became the ninety-first member of the International Red Cross Society. Since its foundation, the Saudi government has supported it financially on an annual basis to help SARCS to achieve its objectives. There are now more than 130 stations in Saudi Arabia to provide the emergency service and medical care needed.

The Central Radio Communication Room (CRCR) is the first part in the system that receives the demand calls. When the CRCR receives a call, the CRCR assigns the call to the station responsible for serving that area. Then the specific station dispatches one of its ambulances. If there is no available vehicle, then the CRCR assigns the call to any other station, based on their judgement. Calls are served on a first come first served basis.

Seven ambulance stations have existed for a long time and each serves some designated quarters. Five of these stations are rented, while the EMS authority owns stations in quarters 17 and 21. The numbers in Figure 1 represent the quarter identification numbers, all of which were used as potential stations. The bold lines represent the boundaries of each station, the location of which is indicated by boxes around the quarter identification numbers.

When staff of the CRCR communicate with other callers regarding an incident, they usually fill out a form consisting of the following:

a) Date and time of receiving the call.

b) Information regarding the patient.

c) Location of the incident.

d) Times of the following:

1) Receiving the call by the CRCR.

2) Receiving the call by the specific station.

3) Dispatching an ambulance.

4) Arrival to the scene.

5) Pick up time at the scene and moving to the hospital (if required to be transferred.)

6) Arrival at the hospital (drop- off time.)

7) Arrival at the station (station).

Staff of the CRCR usually do not write the time when ambulances arrive at their bases, because once an ambulance drops off a patient in hospital, this ambulance is considered ready to receive another call while on the way back to its station.

The government's policy on thrift means that new projects or expansion of existing ones should be studied to make sure that there is no wastage involved. At the time of the study, the Emergency Medical Service (EMS) in Riyadh was intending to increase its service to serve a larger demand within a target time. However, the EMS authority has no idea how many stations should be added, where they should be located, and how many ambulances were needed in each station? A model was developed to answer these questions.

Real-World Applications in the literature

The set covering location problems and their extensions have been used extensively in many real-world applications. Models for the Maximal Covering Location Problems (MCLP), Church and ReVelle[2], have been applied to both the public sector and private sectors. In the public sector it has been applied to fire services, EMS, bus stops, among others. In the private sector, it has been applied to locating a company to increase the market share, and can be applied to locate pizza shops, computer services, and mail deliveries to ensure that the service is delivered within pre-specified time. A review of this model can be found in Marianov and Revelle[3].

Eaton et al.[4] used the MCLP model to determine optimal centres for which to recruit rural health workers and ambulances in Valle Del Cauca, Colombia. Due to the unavailability of an integer programming code they used a greedy adding and substitution heuristic. Eaton et al.[5] used the MCLP model to analyse options for EMS vehicle deployment in Austin, Texas, in terms of equity, efficiency, effectiveness measures and opportunity costs associated with administrative alternatives. The use of the MCLP formulation allowed the analysis of a variety of policy options, including changes in the number of vehicles, the response time used to define coverage, and the allowable candidate vehicle locations. The plan implemented during 1980-83 resulted in \$3.4m savings in construction costs and over \$1.2m savings in annual operating costs. Later, Eaton et al.[6] applied a multiobjective formulation to determine the optimal locations of emergency medical services in Santo Domingo, Dominican Republic. They utilised the hierarchical objective set covering formulation of Daskin and Stern[7]. In the application, the model aimed to maximise the multiple coverage, given that each node is covered at least once. The problem was solved in two steps using a multiobjective heuristic, since no integer or linear programming codes were available to the authors at that time.

Daskin's[8] maximum expected coverage location problem (MEXCLP) model was applied by Fujiwara et al.[9] to locate the EMS in Bangkok, the capital of Thailand. The 'good' solutions obtained were further analysed by a simulation model, since the model does not give an optimal solution. Nevertheless, Fujiwara et al.[10] used MEXCLP along with the probabilistic central facility location model of Aly and White[11] to screen the large number of possible alternatives, which were also subjected to a detailed analysis by simulation.

In the United States, Goldberg et al.[12] developed and applied a non-linear integer programming model for finding optimal base locations of the EMS in Tucson, AZ. This model had the single objective of maximising the expected number of calls served in 8 minutes. The formulation takes into account the stochastic travel times, multiple call classes and the probability of vehicles being busy. They used the pairwise interchange methods for finding heuristic solutions for the problem, to narrow the possible sets of base locations to a few locations. Once these few candidate sets are determined they can be simulated using discrete event simulation[13].

Zhu and McKnew[14] applied their model, the Workload Balancing Allocation Model, to balance workloads of ambulance personnel in Shanghai, whilst ensuring that any geographical area is likely to have an ambulance available within reasonable time limits. It aims to allocate a fixed number of ambulances to previously defined locations so that the ambulances at different locations are, nearly, equally utilized. The model explicitly addresses the issue of equalizing workload by utilizing a goal programming approach and incorporating a dispatch preference matrix for those stations capable of covering each demand point.

The maximal direct covering tree problem, a special case of MCLP, may be used in many real world applications, Hutson and ReVelle[15], such as transportation networks (siting roads, railway tracks, shipping and air lanes) and communication systems (designing television systems, leased-line telephone networks, aspects of teleprocessing and computer systems).

Other studies of relevance, but which do not use the MCLP formulation, include that by Serra and Marianov[16] who were concerned with locating fire stations in Barcelona. They used a formulation based on the *p*-median model[17,18] to address the issue of locating new facilities when there is uncertainty in demand, travel times or distance. Badri et al.[19] also studied where to locate fire stations: this time in Dubai. They developed a multi-objective model using integer goal programming. Mendonça and Morabito[20] analysed the deployment of an EMS on the highway connecting São Paulo and Rio de Janeiro in Brazil. They applied the hypercube model[21] to evaluate the mean response time to an emergency call. The results showed that the workload imbalance between ambulances could be reduced. Harewood[22] applies a multi-objective version of ReVelle and Hogan's Maximum Availability Location Problem (MALP)[23] to find good locations for the Barbados Emergency Ambulance Service.

Groom[24] described the use of a general queueing model to measure the performance of the West Glamorgan Area Health Authority, in the UK. This model estimates the response time distributions given by different arrangements of ambulances and operating conditions.

Developing a model for Riyadh

The decision-makers of the Saudi Arabian Red Crescent Society (SARCS) were contacted, and the general vice president agreed that the data needed would be made available. The head of the CRCR gave the opportunity to enter the CRCR at any time and to collect or ask for any information. However, the task was not straightforward, as it was necessary to collect manually all the information. It would have been easier if they had a computer at the CRCR as the information is usually written on forms and stored in files.

The EMS receives more than 13000 calls on average a year (36 calls a day) using seven centres and about 35 ambulances. The EMS system is a self-contained system, because each station is responsible only for those demands within its boundary.

Data for developing and estimating the model coefficients were collected from April 15 to July 29, 1996. The area was divided into 92 quarters, as in the CRCR records. Detailed information for more than 3800 incidents was collected. This information covers about three and a half months. For each call the first six times in the list given earlier were collected and rounded to the nearest minute. Demand per quarter and the service time per call for each quarter were collected.

Travel time modelling

The distances or travel time between each pair of quarters needs to be estimated. A number of different ways have been suggested.

Benveniste[25], indicated that the travel distances between each potential station-quarter pair can be measured by using either rectilinear or Euclidean metric. For instance, if a potential station is located at (x_k, y_k) and a quarter is located at (x, y), then the distance (e.g. $d(x, y, x_k, y_k)$) between this station and the quarter is measured as follows:

Rectilinear: $d(x, y, x_k, y_k) = |x - x_k| + |y - y_k|$

Euclidean: $d(x, y, x_k, y_k) = [(x-x_k)^2 + (y-y_k)^2]^{1/2}$

Fitzsimmons[26] also used rectilinear displacement in the x, y co-ordinate points of departure and arrival to estimate travel distances. Eaton et al.[6] used a different approach to find travel distances and travel times, consisting of seven steps:

1. Nodes were designated at the centre of each quarter.
2. All reasonable routes between neighbouring nodes were identified.
3. Each route was classified into 16 types of traffic arteries.

4. Long routes were divided into shorter routes based on their type.

5. Drivers of ambulances estimated travel speed among these routes.

6. Expected mean travel speed along each type of traffic artery was estimated.

7. To compute the expected travel time between adjacent nodes, average speeds were multiplied by the measured length of each arc.

Then, after building up the whole travel time network, a shortest-path algorithm was used to compute the expected shortest time of travel between any pairs of nodes.

Kolesar et al.[27] estimated the average fire engine travel time as follows:

$$T(D) = \begin{cases} 2(D/a)^{1/2} & \text{if} \quad D \le s \\ (v/a) + (D/v) & \text{if} \quad D > s \end{cases}$$

where;

T(D): is the travel time.

D: is the travel distance.

a: is the acceleration.

v: is the cruising velocity.

s: is the distance required to achieve cruising velocity.

Perez[28] assumed travel time for an ambulance to be two-thirds of that for conventional vehicles. This value was based on the opinion of several ambulance providers in the area.

Fujiwara et al.[9] estimated distances to be a constant multiplied by the Euclidean distances. This constant is estimated using linear regression. After determining the travel distances, the travel times were estimated using the square root law. This is similar to Kolesar et al.[27] (1975), and depends on an acceleration speed phase, a cruising speed phase, and a decelerating phase. This may be written mathematically as follows:

$$E(t) = \begin{cases} c\sqrt{D} & \text{if} \quad D < s \\ a+bD & \text{if} \quad D \geq s \end{cases}$$

where,

E (t): expected travel time to cover a distance *D*.

s: is the distance required to achieve cruising speed.

a , *b, c* and s are empirically estimated.

Goldberg et al.[12,13,29] used piece-wise linear regression to estimate the travel times.

In this context, the probability of an ambulance located at an existing station arriving at its service area within a specified time needs to be determined. However, the probability of an ambulance located at a potential station arriving to a service area within a specified time cannot be calculated, because of the absence of empirical data. Therefore, another way of estimating this information was needed. With the help of The Higher Commission for the Development of Arriyadh (HCDA), travel times between quarter-quarter pairs were estimated. These travel times are obtained using special computer software called EMME/2 designed for traffic and planning studies[30]. It requires a large amount of data of an existing network when used for planning. It tries to closely approximate the real-world conditions. It requires a full description of the existing network representation such as traffic surveys of all quarters, road characteristics, and accident statistics. In addition, the existing traffic characteristics of roadway or transit links such as volumes, travel times and speeds can be input for evaluation. The data of a network representation can be put in by co-ordinates, or it can be digitised from a map. Up to 30 modes of travel can be input for different types of transit vehicles.

The equilibrium (capacity constrained) auto traffic assignment problem may be solved by the linear approximation algorithm. The behavioural assumption, on which the equilibrium traffic assignment problem is built, is that each driver chooses the route that he perceives to be the best. When each driver cannot improve his travel time by changing his route, then the equilibrium is achieved. In other words, the "driver optimal" is achieved when no driver can improve his travel time by changing the route. The equilibrium traffic assignment corresponds to a set of flows such that all paths used between an origin-destination pair are of equal time.

The output of this software is comprehensive. It includes the travel time among all nodes within the networks and can be used in traffic simulation models for the establishment of signal settings. Economic evaluation, traffic impact analysis, and evaluation of network performance are optional outputs. Possible outputs are essentially unlimited since the software has an open architecture that allows numerous specialised analysis procedures to be built.

Using the data from the CRCR records, the travel times from each of the existing station-quarter pairs were obtained. These travel times were converted to probabilities of arriving within the target time (i.e. 10 minutes) for the existing station-quarter pairs, by generating cumulative curves of number of calls reached within the target times (i.e. 10 minutes or less). Furthermore, to make these estimations more reliable, only the station-quarter pairs that have at least 30 calls were used. These results are the dependent variables values (i.e. y), which will be used in a regression model to determine the probabilities of travelling within the target time among quarter-quarter pairs for the whole city. Travel times among quarter-quarter pairs for the whole city are obtained from the EMME/2 software package. Therefore, the probability of covering a specific node was estimated in two ways. First, the probability of covering a quarter from its existing station was determined during the period of monitoring the system as described earlier. Second, the probability of covering a quarter from its potential station was estimated by combining empirical data and the results obtained by the EMME/2 software package.

Estimating probabilities on the basis of observing the probabilities between each quarter-quarter pair would have been expensive in time and resources. For example, to drive only once each quarter-quarter pair requires more than 8 thousand trips. However, to estimate the distribution of probability for every quarter-quarter pair, at least ¼ million trips are required, assuming only 30 observations per quarter-quarter pair. Therefore, a model is needed to estimate the probabilities of arriving within the specific time. Note that a model is important since no data exists regarding the probabilities of arriving within the target time between each potential station-quarter pair.

Whilst other authors[12,13,29] have used regression to estimate travel times, in this context a regression model will be used to derive an approximation for the probabilities of arriving within the specific time. The travel times are selected as independent variables for two reasons. Firstly, the travel times were the only independent variable, since it is the only reasonable data available. Secondly, the travel times incorporate all factors that affect the probabilities of arriving within the specific time. These factors are traffic conditions, speed of an ambulance, time of day, climate conditions, and type of routes. Therefore, the travel times are the only independent variables, while the probability of arriving within the specific time is the dependent variable. The travel time is the independent variable because it causes the probability of arriving to vary. The appropriate tool for finding the relationship between probability of arriving within a specific time and the travel time, which consists of other factors that affect the probability of arriving, is regression analysis.

The observed probabilities were divided into two homogeneous groups. In other words, two simple linear regressions were used to estimate the rest of the probabilities of arriving within the specific time among quarter-quarter pairs. The first group is for the existing stations located at the city centre and old quarters, which have specific similar characteristics such as narrow lanes, heavy traffic, lower speed, and so on. These stations are located at node 21 and node 17. Therefore, the probabilities of arriving within the target time from the potential stations located within the boundary of these quarters were estimated using the result of the first regression model. The second group is for the other stations that may share or experience different characteristics such as wider streets, less traffic, higher speed, and so on. These stations are located outside the city centre. Similarly, the probabilities of arriving from the potential stations located within the boundary of these stations were estimated using the result of the second regression model.

While a linear regression has been used in this context, it is important to consider alternative relationships. These data were tested against linear, logarithmic, inverse, quadratic, cubic and other regression models to see which describes the curve best. Once the best model is found, the second step is to use this model in estimating the relationship. If a non-linear model is appropriate to the actual data, then the probabilities of travel within the specified time can be estimated from the model that has been determined to be the best.

Figure 2 shows a comparison between the probability of arriving within the target time by the first linear regression model and the conventional set covering models. It shows how the probability of covering a demand decreases steadily as the arriving time increases. It starts with the intercept (0.93), and decreases by - 0.058 for each unit time increase. On the other hand, the set covering models assume that any demand within the target time (i.e. 10 minutes) is 100% covered, while others beyond the target time are covered with 0% probability.

The results that are obtained reflect the behaviour of the model. As far as the first goal is concerned, the nodes that can access areas of high demands and with higher probabilities of being accessed will be targeted. The selection of a node to be a base is determined by the value that this selection can add to the objective function. This model tries to increase not only the total demands covered, but also the probability of being covered. Therefore, the selected node must increase both these two factors, or if that is impossible, then increase one of them. The following gives an explanation of the results from the model. The optimal solutions obtained for one location, through to 17 locations, the number required to cover the entire city, are given in Table 1. The demand density map given in Figure 3 will aid interpretation of these results.

For a single station node 22 is selected. There are only two major superhighways that divide the city into four sections: King Fahad Road and Makkah road. Node 22 is located at the intersection of these two major highways. From this node the superhighways allow quick access to most of the city. Therefore, it has been chosen to cover most of the demands within the target time. Furthermore, it is optimal because it is the only place that covers two highly populated clusters. One is in the south towards the city centre (i.e. nodes 1 up to node 21), and the other cluster is in the north of the city centre (i.e. nodes 36, 37, 39, 40 and node 57).

Having placed the first station, node 54 is selected to be the optimal place for the second station. Node 54, located at the far west of the city, contains the largest demand generated at a single node (more than 7% of the total demand). The second station is placed at node 54 not only because of the high demands, but also because of the higher probability of accessing these demands when placed at the node itself.

The third station has been placed at the east of the city, node 69, which is the second node that has the largest demand. It has itself only about 7% of the total demand. In addition, the probability of covering these demands is high since these new covered demands are very close to the new station. The next station is placed at node 10, in the south of the city centre where about 9% of the demand is located. However, the probability of covering these demands is not very high, unlike the station located at node 69, because the demands are not great in quarter

10 itself. In other words, these demands are scattered around node 10, but not within this quarter.

When a fifth node is added to the previous optimal stations, node 54 and node 69 remain, but nodes 8, 14, and 57 replace node 10 and node 22. Node 22 covers two populated areas to the north and to the south of it. It was located in a strategic location that can access motorway intersections. Now, a new station is added to the set, and therefore it will be better if each one of these two areas has a station placed very close to it. A new station is placed at node 57 at the north cluster, while another station is placed at node 8 at the east of the city centre. The station placed at node 8 covers most of the demands generated at the north and east of the city centre, while the demands generated at the south and west of the city centre are not covered by this station. Therefore, the station at node 10 is replaced by a station at node 14 which covers most of the demands generated in the south and west of the city centre. By locating at node 14 the demands located south of the city centre and the demands located at the south-west of the city can be combined. Node 14, while it has only 1% of the demands generated is located on a major motor way intersection that gives it quick access in four directions. This station increased the demands covered by about 6%; up to 81% of the total demands. At the sixth stage, node 42 is chosen as an optimal location to serve another important cluster that is located at the north-east of the city. The station located at node 42 serves quarters 84,79,42,43,44,41, 60, and 61 which cannot be accessed by station 69.

Starting from seven locations, the optimal solution settles down and except for node 57 they do not change for all the next stages. A station located at node 57 in the north-west of the city serves quarters 80,81,82,73-76, 56-59 on the north, and quarters 36 up to 40 on the south.

This station located at node 57 is replaced by a new station at node 75 to serve the quarters at the north, and another station at node 36 to serve quarters at the south.

For comparison, from the results of the model, the existing 7 stations only cover 74% of the population within 10 minutes. If SARCS wish to implement these results they have at least three options: cover the whole city, relocate the existing stations, or increase the number of stations to give a specific service level. The results for these options can be found in Table 1.

To cover the whole city

To cover the whole city, at least 17 stations are needed to satisfy the minimum requirements that any node can be served from a station within at most 10 minutes and within the maximum possible probability of arriving. The locations of these 17 centres are as follows:

Utiqah (14), Alwazarat (22), Almalaz (26), Umalhamam (36), Ashefa (31), Aljazeerah (47), Alorija (54), Almalik Fahad (75), Assewaidy (53), Arrothah (43), Ghernatah (84), Alaskan (48), Alfwaz (51), Annasseem (69), Aljunadriah (63), Alderiiah (86), and Almatar (92). The minimum number of ambulances required are 2, 2, 2, 1, 1, 2, 2, 2, 1, 1, 1, 1, 1, 2, 1, 1, and 1, respectively. Therefore, about 24 ambulances are needed to ensure that any call that arises anywhere at the city will find at least an idle ambulance within 10 minutes driving to serve it.

To Relocate the Seven Existing Stations

Relocating the existing stations will maximise the demands within the target time and will maximise the probability of serving them on time. The following is the optimal set of seven stations: Utiqah(14), Alwazarat(22), Aljazeerah(47), Alorija(54), Arrahmaniah(57), Alquds (42) and Annasseem(69). By relocating the existing seven stations to these quarters, the demands covered will be about 85% of the population, which is an improvement of 11%. Two ambulances are required at each of these locations.

Several quarters (i.e. 35, 48, 49, 50, 51, 62, 63, 67, 82, 85, 86, 87, 88, 90, 91 and 92) are not covered within the target time, but can be assigned to the nearest opened stations. By assigning the uncovered quarters to the nearest opened stations, then the arrival rates will be increased. Therefore, the number of ambulances allocated to each opened base may need to increase too, to keep the same level of performance (i.e. the probability of an ambulance being busy when a call occurs is less than 5%). However, by knowing the assignment of the uncovered quarters, the new allocation of ambulances can be calculated.

To increase the number of stations to give a specific service level

The optimal locations in this option depend on the specific number of the stations desired and can be found from Table 1.

Optimal Locations assuming the existing stations are fixed

Alternatively, the seven existing stations, though not optimal, can be regarded as fixed and optimal solutions, given this constraint, can be found for 8 stations through to 18 stations, which in this scenario are required to cover the entire city. The results are presented in Table 2.

Discussion with SARCS

These results were discussed with SARCS. They requested an investigation of a specific location, whether it is optimal or whether there is a better one. SARCS were interested in locating at a specific building at Almalaz (quarter 26). However, the exact location of the building or street (i.e. within Almalaz quarter) is not dealt with explicitly by the model. The authority of the EMS will decide which building is suitable and available to be a station. If the EMS is given the opportunity to locate anywhere in a quarter, then the existing street network and intersections need to be examined to find the point that minimises shortest paths to all demands covered. However, in reality it is easier to locate somewhere in a quarter but it is more difficult to locate at an exact point. There are many reasons that make it more practical for a model to locate at a quarter instead of location at a specific point. For instance, there may not be a building at the exact point, or if there is a building it may be not suitable because of its size or facilities. In addition, even though you find a suitable building at the exact point, it may not be available to be rented or to be bought. Therefore, the model does not allow finding the exact point, so cannot be used to suggest whether to locate at a specific building or not. However, the model can indicate whether locating at Almalaz is optimal or not.

By adding an additional station at Almalaz (e.g. as a quarter) to the existing seven stations, the maximum expected coverage will increase from 0.559 to 0.60, the population covered will increase from 74% to 79%, and the average probability of arriving to the covered demands will still be the same (i.e. 75%).

However, by locating at Ghobirah (numbered 10), as seen in Table 2, the maximum expected coverage will increase from 0.559 to 0.623, the population covered will increase from 74% to 81%, and the average probability of arriving to the covered demands will increase from 75% to 79%. Ghobirah is the 8^{th} optimal location, which covers the southeast of the city centre. The area around it is a populated area and is relatively far from the existing stations.

There is a logic for the model not locating at Almalaz (numbered 26), simply because there is a large overlap between Almalaz and the existing station Almoraba (station numbered 21).

Manfuha (numbered 12) or Aryan (numbered 44) are two locations which are optimal at this level of coverage, and are robust locations, since they are included in the set of 9 locations and will be optimal until the city is covered completely. In other words, by locating at either Manfuha or Aryan it is ensured that this location will still be an optimal station as long as the distributions of demands persists. Choosing between Manfuha and Aryan depends on your preference. By locating at Manfuha (numbered 12), the maximum expected coverage will increase from 0.559 to 0.619, the population covered will increase from 74% to 80%, and the average probability of arriving to the covered demands will increase from 75% to 76%.

On the other hand, if locating at Aryan (numbered 44), the maximum expected coverage will increase from 0.559 to 0.615, the population covered will increase from 74% to 83%, and the average probability of arriving to the covered demands will decrease from 75% to 73%.

One of the authors visited SARCS some three years after the work was completed. The locations of the stations were still as they were because of budgetary considerations, and because they could not relocate the very old locations to better sites because of long-term rental agreements for five of the sites. However, they adopted another way of maximising the expected coverage of demands within a specified period of time. An ambulance has been located in each optimal location on standby. These ambulances are equipped to deal with many cases at the scene of the incident, without the need to rush the patient to hospital.

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Figure 1 The quarters of Riyadh with the existing SARCS station boundaries

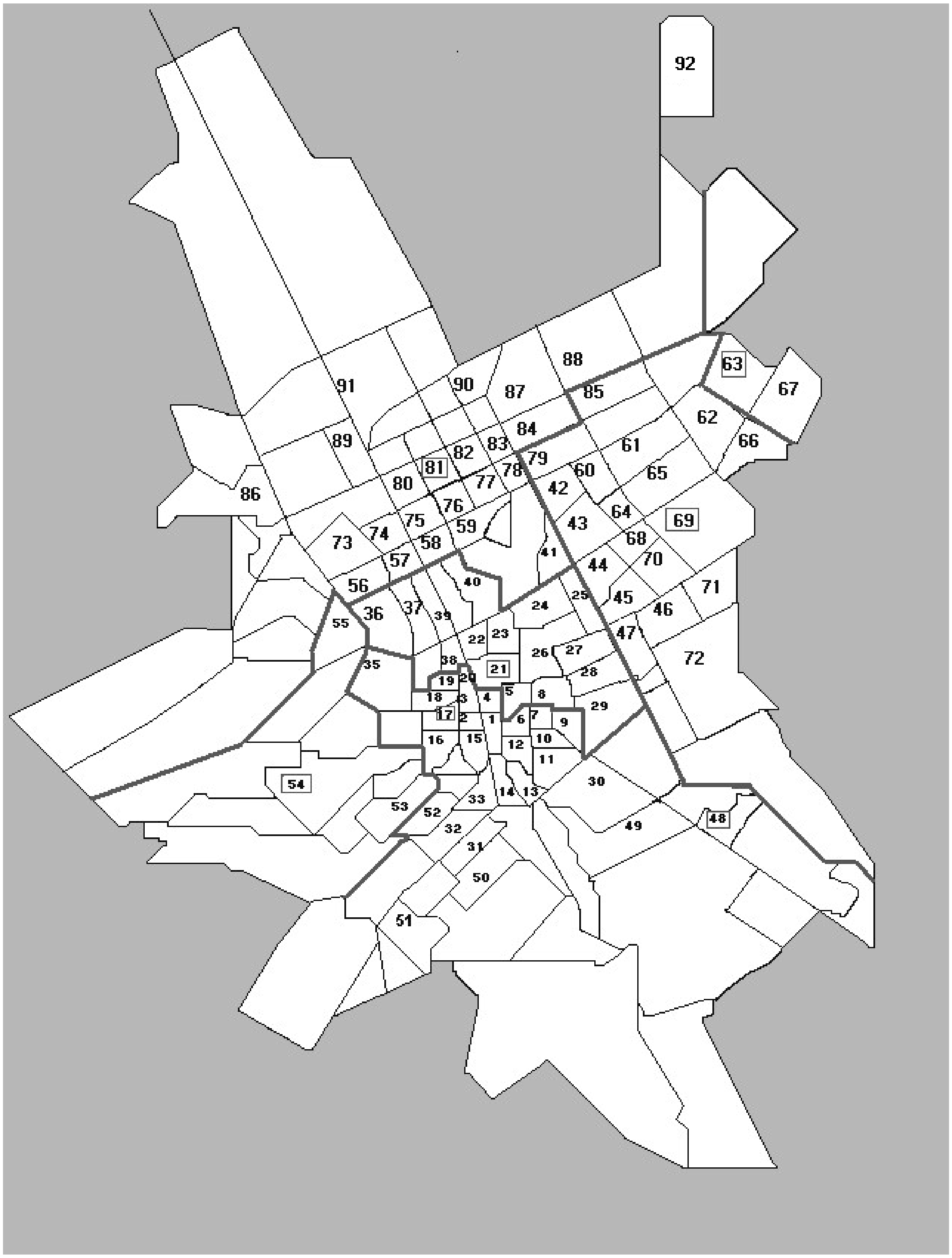

Figure 2: Comparison between linear regression and conventional set covering models

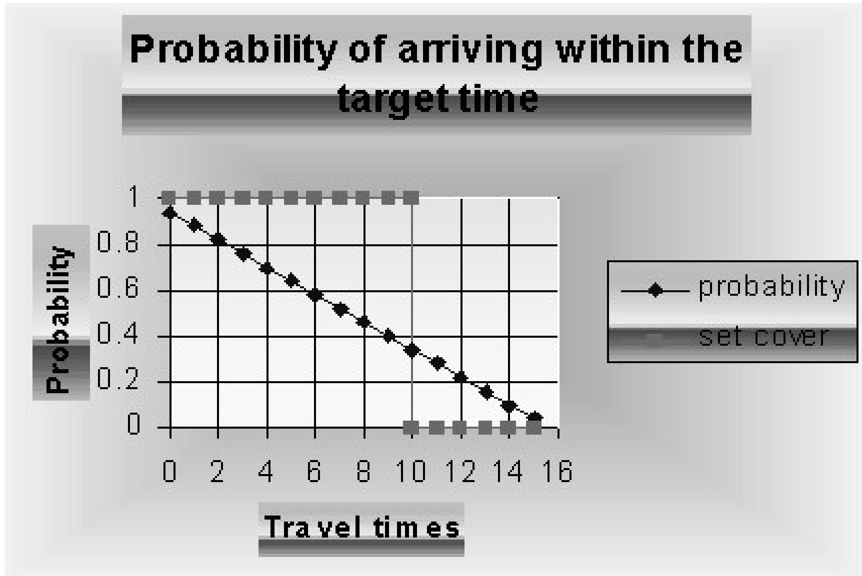

Figure 3: The percentages of the demands generated at all quarters

Table 1: The optimal locations and their objective values

No. of locations	Locations	Maximum Expected demands covered	% of Population covered	Average probability
1	22	0.301	0.448	0.672
2	22,54	0.385	0.566	0.680
3	22,54,69	0.464	0.657	0.706
4	22,54,69,10	0.538	0.742	0.725
5	54,69,8,14,57	0.592	0.810	0.730
6	54,69,8,14,57,42	0.629	0.873	0.721
7	14,22,47,54,57,42,69	0.659	0.853	0.770
8	14,22,31,47,54,57,42,69	0.681	0.861	0.790
9	14,22,31,47,54,57,42,48,69	0.702	0.867	0.810
10	14,22,36,31,47,54,75,42,48,69	0.722	0.887	0.814
11	14,22,26,36,31,47,54,75,42,48,69	0.740	0.918	0.806
12	14,22,26,36,31,47,54,75,42,48,69,63	0.756	0.918	0.823
13	14,22,26,36,31,47,54,75,42,53,48,69,63	0.772	0.934	0.826
14	14,22,26,36,31,47,54,75,42,53,48,69,63,92	0.787	0.948	0.828
15	14,22,26,36,31,47,54,75,53,43,84,48,69,63,92	0.799	0.965	0.828
16	14,22,26,36,31,47,54,75,53,43,84,48,51,69,63,92	0.809	0.978	0.827
17	14,22,26,36,31,47,54,75,53,43,84,48,51,69,63,86,92	0.818	0.99	0.827

Table 2: Summary of the optimal locations (by fixing the existing stations)

No. of locations	Locations	Maximum Expected demands covered
7	17,21,54,81, 48, 69, 63	0.552
8	17,21,54,81,48,69,63,10	0.623
9	17,21,54,81,48,69,63,12,44	0.678
10	17,21,54,81,48,69,63,12,44,47	0.706
11	17,21,54,81,48,69,63,12,47,42,31	0.728
12	17,21,54,81,48,69,63,12,31,47,42,53	0.747
13	17,21,54,81,48,69,63,12,26,31,47,42,53	0.765
14	17,21,54,81,48,69,63,12,26,31,47,42,53,92	0.780
15	17,21,54,81,48,69,63,12,26,36,31,47,42,53,92	0.793
16	17,21,54,81,48,69,63,12,26,36,31,47,53,43,84,92	0.805
17	17,21,54,81,48,69,63,12,26,36,31,47,53,43,84,92,51	0.815
18	17,21,54,81,48,69,63,12,26,36,31,47,53,43,84,92,51,86	0.825