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Toward an Optimal Deployment of Fire Stations in Riyadh, Saudi Arabia

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Abstract. Emergency services which commonly include fire, ambulance, and police services, have geographical distribution characteristics of request of service on one hand and a system of facilities deployed to respond to that request, on the other. Proper deployment of emergency service facilities in an urban environment contributes significantly to the efficiency and effectiveness of providing emergency service. Planning, can contribute to the efficiency and effectiveness of providing emergency services through alternative deployment strategies, *e.g.;* by evaluating the existing and, where necessary, recommending proposed spatial distribution of service facilities within a given urban environment.

The purpose of this paper is to analyze the existing allocation and location of fire service stations in the city of Riyadh and to recommend an alternative strategy for the deployment of fire stations within the city comparing, also, the expected performance of such deployment with those of the present deployment.

For this purpose, the "Parametric Allocation" and "Site Evaluation" models were calibrated to provide the analytical basis for subsequently focusing on the requirements, constraints and results of the tests of those models, along with recommendations for their future applications. The test of models, notwithstanding data problems, have shown that an incremental increase in the number of service stations produces significantly greater level of improvement in the travel times for emergency services and that the methodology employed can help produce definitive strategies regarding deployment of fire services.

Keywords: Emergency Services, Location, Allocation, Site Evaluation, Parametric Allocation Land Use, Time-Distance Relationship.

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Introduction

Effective and efficient provision of emergency services is a principal function of urban governments with implications ranging from rational use of resources for the security and well-being of the urban population to matters of governmental authority. Spatial distribution, *i.e.* allocation and location of emergency service facilities with a given urban setting, contributes significantly to the efficiency and effectiveness of providing emergency services. As any spatial urban phenomenon, spatial distribution and location concern planning. However, until recently, planning concern with spatial distribution of emergency services had been limited to application of rudimentary distribution standards and principles; *e.g.* one service station per given size of population. With the development and use of analytical models, more rational distribution of emergency service facilities have now become possible.

Extensive studies, spanning over some 40-years-period, have provided the background and easy use of analytically-based models and related computer programs originating in the western world[1]. Especially noteworthy among these analytically-based models are those developed and used extensively in the U.S., by the Rand Corporation: Parametric Allocation Model (PAM) and the Site Evaluation Model (SEM)[2]. The use of these models for allocating and locating all emergency service facilities *i.e.* the emergency medical services, fire services, and police services, was suggestive of their potential utility and adaptability for the Saudi Arabian city context.

This paper attempts to formulate a strategy for deployment of fire service stations within the city of Riyadh utilizing the Parametric Allocation Model (PAM) and the Site Evaluation Model (SAM)[3]. It attempts to analyze the existing location/allocation condition of fire stations in the city of Riyadh and to recommend an alternative strategy for allocation and deployment of fire service stations within the city, while comparing the expected performance of such deployment with those of the present deployment. It seeks also to draw the attention of planners and city managers of emergency services to emergency service allocation and location matters. It is hoped that knowledge gained on the issues and problems emanating from the applications and adaptation of these models in a non-Western city context would contribute to knowledge and lead to valuable suggestions for applications of similar nature in other spatial and institutional contexts.

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1. For a good survey of this work see **Carter *et al.***[3], **Kolesar** and **Swersey**[9], **Larson**[10], **Walker**[18], and **P.T.I.**[12].
2. For discussion of the particulars and use of these models. See **Dormont** and **Rider**[14].
3. The latest version so far made available by RAND, of PAM and SEM were used as the basis of this research.These two models were selected as their formulations and data requirements provide a better fit to the operational environment and data presently available in Riyadh. Recent (1994) communication with the authors of these models confirmed our use of the last updated version of the models. Other class of models, *e.g.* the Hypercube Model, are applied in selected U.S. cities where emergency systems and their management are relatively mature; See, **Bradeau** and **Larson.**[1] These types of models represent a further advancement in management and operations and demand an advanced level of service operations and detailed and extensive data which do not exist in the context of emergency services operation in Riyadh.

On the Nature of Fire Services

Fire service is a typical emergency service having all of the attributes that characterize and distinguish this service from other services provided by municipal governments. Some of the attributes of emergency services relevant for the purposes of this paper include the following:[10], [7].

– Emergency services involve incidents that occur throughout the city.

– The time and place of occurrence of the incident cannot be reliably predicted on an individual basis.

– In response to each call for service, one or more emergency service vehicles are sent to the scene of the incident.

– The total time taken by the emergency service vehicle in arriving at the scene of incident from the time of service request has a strong influence on the actual, or perceived, quality of the service provided.

Fire services are performed within a spatial setting, *i.e.,* the urban environment. The urban spatial environment, in conjunction with the socio-economic characteristics of its inhabitants, influence the need for and the efficiency of the delivery of urban emergency services. Since both the urban spatial structure and its demographic patterns cannot be modified easily, the location of service stations (or facilities) must be adapted to the form and characteristics of the urban environment.

The planner's and service provider's concern with fire services involve the determination of the number of service stations, their allocation and location in a given city, observing the spatial and non-spatial characteristics of this service, including also specification of performance measures that will be used in "optimizing" the deployment of facilities. The deployment strategy will seek "optimization" in response to the primary objective of fire service which is: *to minimize the loss of life and property caused by fire.* The performance measures to be employed may include such items as adequate level of fire protection; acceptable fire risk; costs; availability of fire companies; fire company work-load; response time[4].[16], [18].

Of all these performance measures response time, which is defined as the period of time from the moment the fire department is notified until a fire company is ready to operate at the scene of incident, has been the central theme of any fire service deployment policy. This is primarily due to the time-dependent nature of fire service activities, as shown by Fig. 1, below. Specifically, minimizing the response time would be expected to reduce life and property losses from fires.

It is the response time which forms the basis of "performance objectives" that have been tested in the models as explained below.

4. It should be noted that neither the adequacy of fire protection nor the level of acceptable risk are specific quantifiable performance measures against which alternative fire protection policies and station locations can be evaluated. Cost of service can be considered a performance measure if it allows for evaluation of the effect of alternative policies given equal resources, *i.e.,* equal costs.The availability of fire companies in the event of fire, is based on the assumption that a fire company is available and that travel time to the site of fire is minimized. Fire company work load refers to the average number of times per day that a fire company responds to alarms, or the average period of time it spends at the scene of a fire.

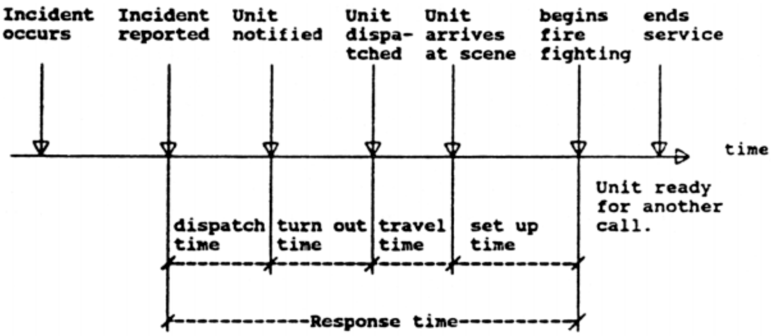

Fig. 1. Time-dependent fire service activities, Carter, G., Ignall, E. & Walker, W. (1975.

Methodology, Model Calibration and Results

The efficient delivery of fire services (or, emergency services in general) depends primarily on two variables: first, the geographical distribution of the demand for fire services and second, the time it takes to deliver that service. The Parametric Allocation Model (PAM) used in this study, focuses on the allocation of a given number of fire service units to the pre-designated geographical zones of service. The model operates on the basis of a trade-off parameter which emphasizes the selected performance objectives. The two commonly used performance objectives are :

equalizing of average time to incidence in each protection zone and, minimizing the average travel time to all incidences throughout the city.

The model can be used to evaluate allocation proposals and to predict the values of the performance measures resulting from the proposed pattern of allocation. Given the value of the performance objective, the model can also be used to determine the best allocation of a given number of service units to protection zones. The Site Evaluation Model (SEM) receives the number of units to be allocated from the Parametric Allocation Model (PAM) and proceeds to evaluate the adequacy of the fire station units within each location of protection zone as well as possible consequences of arrangement of units with respect to one another.

The use and calibration of these models, in order to provide alternative strategies for the deployment of emergency service facilities in any city or region, requires the collection of (or have readily available) sufficient data to estimate geographical demand and/or risk profile[5]. In addition, it is necessary to have readily available an estimate as to the length of time required for a vehicle to traverse specified distances while responding to requests for service (*i.e.,* a time versus distance relationship).

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5. Although data limitations usually exists in performing such an analysis, sufficient data have been made available through Arriyadh Development Authority (ADA) and the efforts of the researchers under the auspices of KACST Project AR-6-111. These primary data collected and secondary data available will be discussed in addition to their appropriate application. Through this analysis, it is hoped that the direction will be pointed in which further development must progress so that improvements in subsequent analysis may be realized.

With respect to potential risk analysis, geographically-based demand analysis is essential. Analysis of risk may not be based upon a known uniform, geographically distributed catchment area but, rather, is based upon an assessment of the prospects or probabilities of future demand and the potential hazards in not providing proper fire service to a given area. For example, it may be the case that a hospital or a school historically has had little demand for fire services; yet, the potential hazards being risked in not providing adequate service to such a facility are very great due to the high population densities associated with such a facility.

Land use data, here, provides the best data source in order to obtain an estimate of the present risk for fire services. For the City of Riyadh, land-use data stratified at the sub-municipality and sub-hara levels were made available on the Urban Intelligence System of the Arriyadh Development Authority (ADA). ADA's land use, information survey of 1990 was used to derive the index values that were subsequently used in determining "homogenous, potential demand – hazard" zones.

In addition, further information of considerable value in this analysis, including the overall demand rate of requests for service on a city-wide basis[6], were made available. Both were sufficient to determine a peak hour demand rate for the city of Riyadh and to estimate a geographical risk profile over the city of Riyadh, based upon the spatial distribution of land uses over the city, as stratified by the 585 sub-haras delineated in the city. (See, Fig. 2 for a map of Riyadh depicting the relative risk of each sub-hara as computed). These data are necessary requirements in employing any model to determine an optimal deployment of fire fighting services.

In addition to potential risk analysis, time versus distance relationships are required (in order to provide adequate assessment of the delivery time of services) for the operation of the models. The time versus distance relationship can vary somewhat from one city to another, seemingly based upon the structural arrangement of the city's street patterns, particularly upon the nature of the hierarchical street network as well as traffic volumes, road conditions and geometric design characteristics of roads. This may be particularly true in the case of the city of Riyadh with its varied traditional, grid, and special urban patterns. Prototype data representative of the time distance relationships for the city of Riyadh was provided.[7] In the Riyadh setting, it was necessary to derive several relationship between time and distance, one relationship to be established for each area of the city with similar land-use characteristics and street configurations. The classification technique known as single linking was employed in order to categorize sub-municipalities within the city[6].

Riyadh may resemble, in some areas[8], other cities in various ways particularly if the entire metropolitan area is examined, including suburbs, and hence, similar time versus

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6. This information was gathered directly from the Riyadh Civil Defense Department through interviews with the officials.
7. The city's haras and sub-haras were classified in accordance with their street pattern and a sample of these sub-haras was selected. 267 observations were made in 5 sample haras. The data collected included time, distance and street conditions.
8. Specifically, the city of Riyadh includes extensive urban areas of relatively low density development not unlike that of a typical suburban development in an American setting.

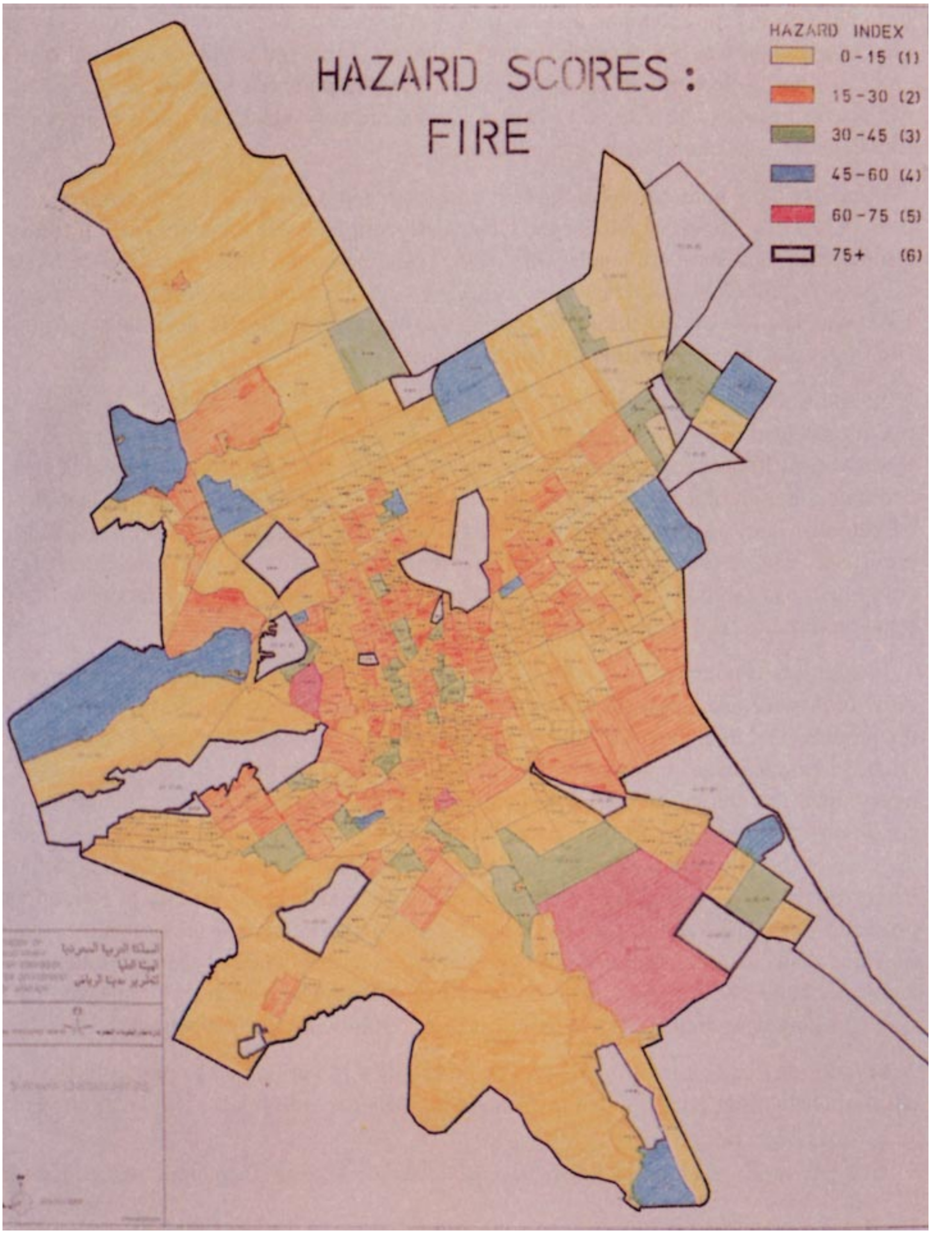

FIG. 2. Computed risked stratified by sub-hara for Riyadh city.

Source: (Based on land use data of 1990, provided by the ADA and indices of risk as determined through consultation with fire service officials in Riyadh).

distance relationships to those applied in other cities.[9] However, due to differences in urban districting in Saudi metropolitan areas, which in turn affect the services time versus distance relationships, it is necessary to take these differences into consideration. A single equation relating time to distance may be a reasonable assumption in the American setting, for example, but may not be reasonable in the Riyadh setting.

As such, the approach to the use of the models has to be modified from single step analysis, which produces an optimal solution, to a multi-step analysis, using the same model, to accommodate the distinctively different characteristics of separate areas within the city of Riyadh. The solutions expected from this approach are optimal for the respective area and their serving stations.[10]

Important to the use of the models is the functional form of the relationships. There are two models used in analysis, the Parametric Allocation Model (PAM), which considers only a multiplicative relationship between time and distance, and the Site Evaluation Model (SEM), which implements a piece-wise square-root/linear (spline) fit to obtain the time versus distance relationship.

A research group at the Rand Corporation has determined that :

> “The functional form that we have found to be most useful provides a square-root relationship between time and distance up to some distance, d, and a linear relationship for distances greater than d.”[7, p. 13]

The use of the models is governed also by the specific service delivery criteria defined by the management of the emergency service. In order to determine a proper deployment of emergency service facilities for the fire fighting service in the city of Riyadh, performance criteria for evaluation of the level of service had to be established. The criteria, as utilized for the purposes of analysis, were stated by the Civil Defense Department as follows: “for 90% of all types of calls within cities, a fire truck should arrive at the scene within 7 to 10 minutes of the receipt of the request by the dispatcher”. Information obtained from personnel at the Riyadh Civil Defense Department enables one to compute an average peak hour request rate on a city wide basis.

Since the PAM model[11] operates as an analytical (non-linear programming) model, the model computes an average travel time (and average travel distance) to requests for service. And, since the PAM acts as an analytical model, rather than a simulation model, computing the 90th percentile of the distribution of the time required to respond to

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9. For example, in particular cases, the use of time versus distance relationship resulted from the successful calibration, testing and application of analytical computer models in selected American cities.[7]
10. The model requires a single time/distance relationship equation. Alternatively, therefore, an approximation of all separate areas could be used. This provides a city-wide solution that is sub-optimal for each of the respective areas.
11. The computer model to be employed in such an analysis must reflect the data available – the variables specified and their degree of specificity. The PAM model satisfies this criteria respecting the limitations of the data available[9]. Thus, the PAM was chosen as the model to be employed in attempting to ascertain a “general picture” of the number of facilities and location of facilities to be employed in the city of Riyadh in order to meet specified criteria.

all requests cannot be accomplished without required to respond to all requests cannot be accomplished without further information. Specifically, one must determine the average response time that would approximate a normal distribution having the 90th percentile lying at X minutes (the value of the operational criteria). Data collected in the time versus distance experiment previously mentioned showed a coefficient of variation (ratio of sample standard deviation to sample mean) equal to 0.389.

In consideration of the operational criteria of desiring to arrive at the scene of incident within 7 minutes (in 90% of these requests) from the time of receipt of the request by the dispatcher, if feasible, or within 10 minutes as an absolute upper limit, results in the following average travel time:

4.67 min. average for the 7 – minute standard
and 6.68 min. average for the 10 – minute standard.

Thus, an average travel time of 4.67 minutes will result in 90% of the requests for service being met within 7.0 minutes, and an average travel time of 6.68 minutes will result in 90% of the requests for service being met within 10 minutes.

Given the average travel time to an incident of 4.67 minutes or less, the objective of the analysis becomes one of determining the number, and location of fire stations such that the overall city-wide travel time is under 4.67 minutes. The multiplicative curve fits for the time versus distance experiment[12] for several Riyadh haras are shown in Table 1.

TABLE 1. Time versus distance travelled multiplicative curve fits for areas of Riyadh.

Sub-municipality grouping	Sample size	Parameters (a)	$[T = a^b \sqrt{D}]$ (b)
Group 1: Olaya	50	1.10	0.95
Group 2: Shumaisi Malaz and Batha Ma'ather and D.Q. Eraijah and Al-Naseem Al-Hair and Ergah Dariyah	123	.98	1.15
Group 3: Al-Oraidh Far North and Northeast	50	1.10	.95
Group 4: North and Roudah Sinaieyah and South East and Itaigah	50	1.10	.95
Group 5: Manfouhah	94	2.43	1.53

The PAM model is well-suited to enabling one to arrive at a solution to the problem under consideration. The model permits the specification of a set number of facilities to be deployed over the city and computes the optimal location of the facilities and the av-

12. Conducted under the auspices of KACST Project AR-6-611.

erage travel time to the scene of incident. For the city of Riyadh 27 facilities deployed as specified in Table 2, with approximate geographical deployment shown in Figure 3, resulted in the average expected travel time as shown. The time standard of 4.67 minutes average response time could be met in almost the entire city while employing a moderate number of facilities. However, due to the disadvantageous time versus distance relationship, as computed as being characteristic of the Manfouhah sub-municipality, the higher time standard of 6.68 minutes was employed. This required 6 units to be deployed in the Manfouhah sub-municipality. (See, Table 3 for the resulting average times and distances for each sub-municipality as computed by the PAM).

TABLE 2. Computed optimal deployment from the Parametric Allocation Model for fire stations in Riyadh (Number of Stations: 27).

Sub-municipality	Hara	Sub-hara
Shumaisi	06	01
Olaya	08	07
Malaz	02	02
Ma'ather	07	03
Eraigah	02	05
Eraigah	12	02
North	12	04
North	15	04
Al-Roudah	08	02
Al-Nasseem	05	04
Sinaieyah	03	01
Sinaieyah	06	01
South	05	01
Manfouhah	02	01
Manfouhah	04	01
Manfouhah	04	03
Manfouhah	05	04
Manfouhah	08	02
Manfouhah	10	01
Itaigah	05	01
Itaigah	08	01
Al-Oraidh	01	04
Al-Hair	01	03
Far North	01	03
East	03	01
East	06	02
Northeast	01	01

One will notice that the facilities to be deployed in each district of the city are non-integer numbers. The physical interpretation of a fractional number of emergency units to be allocated to a district relates to the ability of units deployed in a district to cross district boundaries in order to service requests more closely located than to any other unit. For example, the 0.68 unit allocation to be assigned to sub-municipality Malaz indicates that one unit would be deployed within its boundaries in such a manner that 60% of its responses would be to requests within the sub-municipality boundaries of its deployment and 32% to sub-municipalities outside of its boundaries.

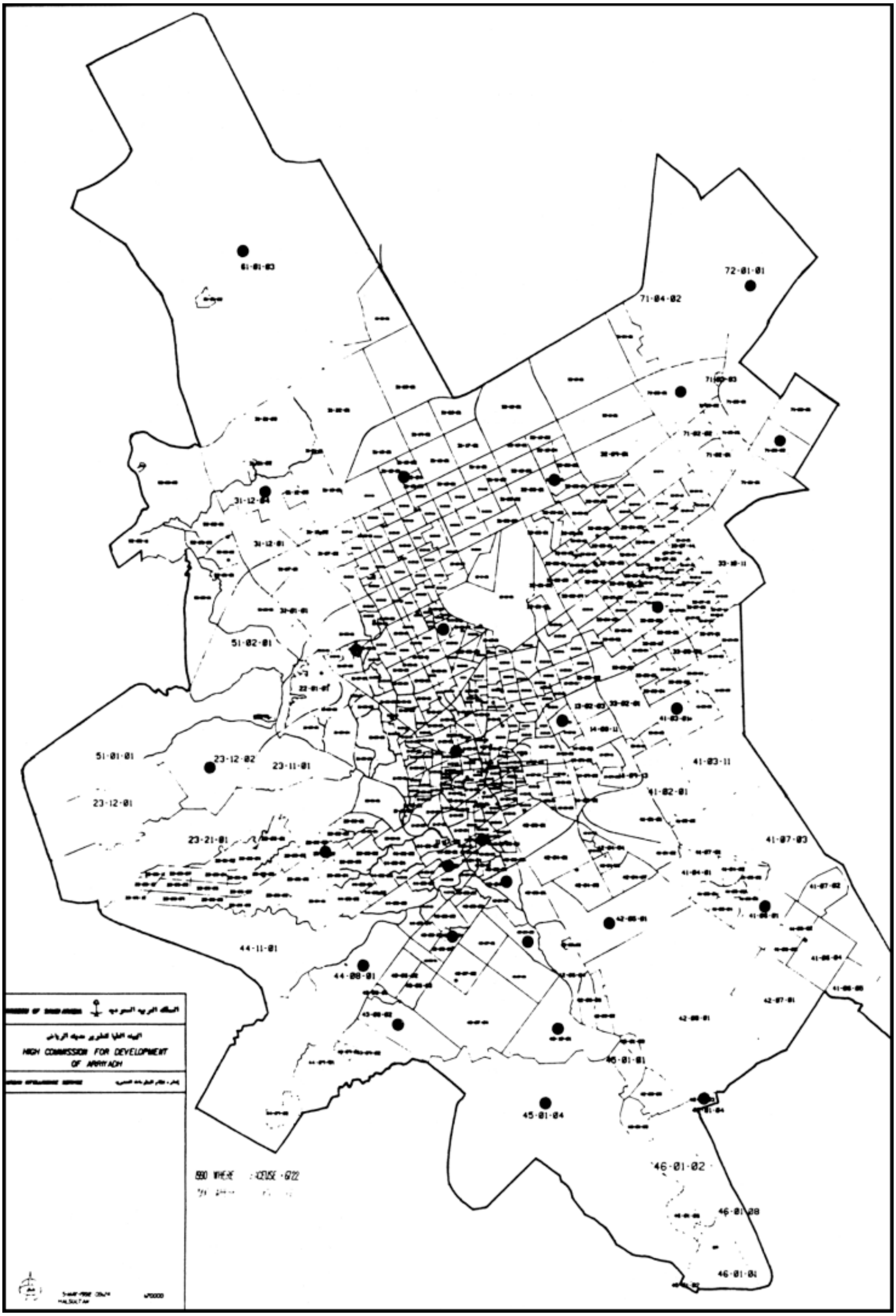

FIG. 3. Proposed deployment of fire stations in Riyadh city.
Source: Based on model test results.

TABLE 3. An optimal allocation and deployment of fire fighting facilities for the city of Riyadh.

Sub-municipality	Number of facilities	Average travel time (min.)	Average travel distance (km)
Olaya	1.00	3.70	3.58
Shumaisi	1.08	2.94	2.60
Malaz	0.68	3.70	3.18
Batha	0.42	4.59	3.83
Ma'ther	0.76	4.12	3.448
Diplomatic Quarter	0.29	3.11	2.73
Erigah	1.31	7.15	5.63
Al-Nasseem	0.94	5.11	4.21
Al-Hair	0.47	5.08	4.18
Erigah	0.61	6.69	5.32
Dariyah	0.45	4.88	4.04
Al-Oraidh	1.19	4.77	4.69
Far North	1.04	4.14	4.04
Northeast	0.77	3.08	2.96
North	2.38	4.25	4.15
Roudah	1.33	4.76	4.67
Sinaieiah	1.49	5.32	5.26
South	1.35	4.84	4.75
East	1.74	4.14	4.03
Itaigah	1.71	4.07	3.96
Manfouhah	6.00	5.97	1.80

Comparison between Proposed Optimal Deployment and Present Deployment of Fire Fighting Service Facilities

The Site Evaluation Model (SAM) provides the means for comparing alternate deployments of fire stations geographically over an urban area. Thus, the SEM was employed in order to compare the proposed 27 facility deployment, as determined using the PAM, with 20 facility deployment presently in operation.

In order to employ the SEM, the exact locations of all of the proposed and present fire stations must be specified on a coordinate grid. Imposing the assumption, as required by the SEM, that the facilities can be located only at the centroids of the demand areas to be studied forces a slight approximation upon the specification of deployment. However, very precise and accurate data concerning the locations of the 585 sub-haras of Riyadh provide for low error in the specification of the locations of facilities. Using the coordinates of the centroid of the sub-hara at the furthest point to the south and west (of the origin of the coordinate system) of the city enables one to specify the distance (to the nearest meter) of all of the centroids of the 585 sub-haras with respect to the origin, and hence, with respect to each other. See Figures 3 and 4 for maps showing the locations of the proposed and present facilities, respectively.

The SEM further requires a time versus distance relationship to be specified and applied to the entire urban area. Thus, in order to determine an overall curve fit, character-

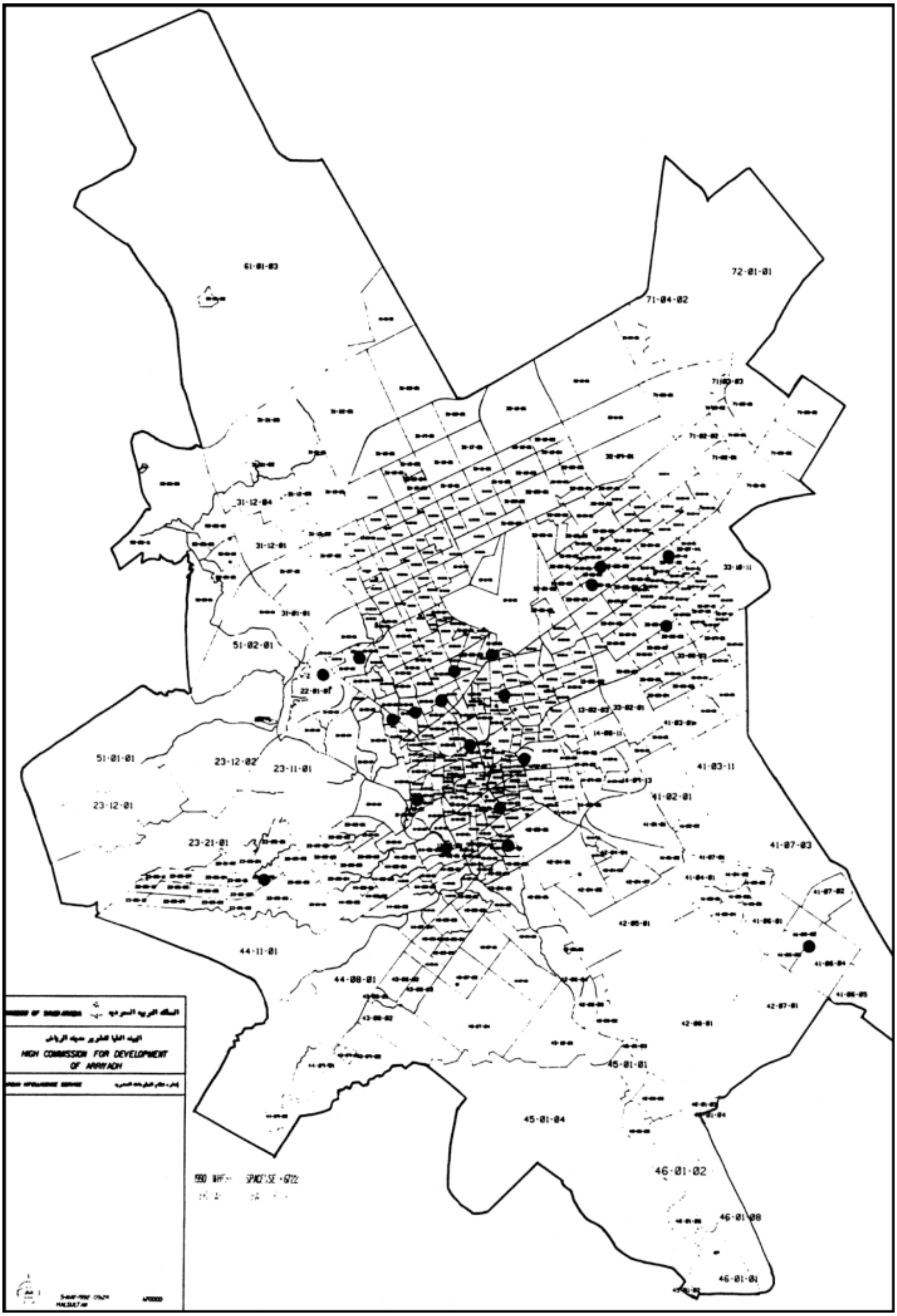

FIG. 4. Existing deployment of fire stations in Riyadh city.
Source: Riyadh fire department.

izing the relationship between time and distance for the entire city, the urban area must be treated homogeneously (*i.e.,* the travel characteristics are assumed to be the same at all points over the city). This is a simplifying assumption which does not appear to hold for the city of Riyadh, as demonstrated by the information provided in Table 1. However, for the purposes of comparing SEM runs, this assumption may be reasonable, though results from the PAM should not be compared to results from the SEM.

The SEM require a spline (piece-wise square root and linear) curve fit, rather than a multiplicative curve fit. For the city of Riyadh a spline curve fit was computed, with the parameters as follows:

$$T = a\sqrt{d}$$

$$T = 2.16\sqrt{D},\ D \le 2.16$$

$$T = a + b \times D$$

$$T = 0.48 + 2.41 \times D, D \ge 2.16$$

Where: T = Travel time in minutes
D = Distance traveled in kms.
a, b = Constants

The resulting average times and distances for the proposed and the present deployments are shown in Table 4.

Table 4. Site evaluation model results for present and proposed deployment of fire fighting facilities in Riyadh.

Deployment	Average travel time [min.]	Average travel distance [km]	Maximum travel time [mins.]
Present (20 stations)	10.64	4.41	58.48
Proposed (20 stations)	7.92	3.24	27.51

General Conclusions and Recommendations

In studying the data available related to assessing the fire fighting service provision within the city of Riyadh, it seems appropriate to conclude that the data available are inadequate in order to provide a definitive optimal geographic deployment of facilities. The data which have been identified as lacking are the following :

1. A geographical demand profile over the city of Riyadh.
2. Actual data points which could be analyzed to relate time to distance traveled in responding to requests for fire fighting service within the city of Riyadh, preferably with these data points stratified at the sub-hara level of aggregation.

Without these data, it was necessary to collect some primary data in order to compute time versus distance relationships and to employ an analysis of risk in order to arrive at conclusions and make recommendations.

Obviously, such conclusions and recommendations will be somewhat tentative, but can demonstrate that the methodology employed is capable of arriving at definitive conclusions and recommendations when the aforementioned data become available.

While the P.A.M. is adequate in providing a “general picture” of how an optimal deployment of fire fighting service facilities in Riyadh might appear, it is inadequate in determining specific optimal sites for facilities. In order to employ computer models which would provide greater specificity in an optimal deployment, more specific data is required.

The employment of the Site Evaluation Model (S.E.M.) requires precise information, including the following :

1. The geographical location of each city block within Riyadh (using a coordinate grid system).
2. The number of requests for service that occurred in each city block over a reasonable length of time.

In order to gain information concerning the second piece of information, it is necessary to collect data related to requests for service organized by street name and building number. At the present time, numbers have not been assigned to buildings within the city of Riyadh. In fact, many residential streets have not yet been assigned names. Thus, before adequate data can be collected to use more powerful computer models, it is necessary to provide basic spatial identification mechanisms (*i.e.*, street names and building numbers).

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نحـو تخصيـص أمثـل لمواقـع محطـات الإطفـاء في الريـاض بالمملكة العربية السعودية

محمد سعيد مصلي ، هوارد برادشر فريدريك
خليل إبراهيم شانلي و فيصل محمد التميمي
كلية العمارة والتخطيط ، جامعة الملك سعود
الريـــــاض - المملكة العربية السعودية

المستخلص . خدمات الطوارئ والتي عادة ماتضم خدمات مثل الإطفاء والإسعاف والأمن تتميز جميعها من ناحية واحدة بالتوزيع الجغرافي والمكاني لتقديم خدماتها وكذلك على أنظمة خدمات يتم تخصيصها للاستجابة لطلب الخدمة من ناحية أخرى . التخصيص الفعال لمواقع خدمات الطوارئ في البيئة العمرانية يسهم في كفاءة وفعالية توفير خدمات الطوارئ . التخطيط يمكنه الإسهام في تقديم خدمات الطوارئ من خلال تخصيص بدائل استراتيجية ، على سبيل المثال ، بتقييم الوضع الراهن للخدمات ، وحينما يتطلب الأمر التوصية بالتوزيع المكاني لخدمات الطوارئ في البيئة العمرانية سيعمل على زيادة فعاليتها وكفائتها .

هدف هذه الورقة هو تحليل الوضع الراهن للتوزيع المكاني ونشر محطات الإطفاء في مدينة الرياض ، واقتراح استراتيجية بديلة لمواقع محطات الإطفاء في المدينة مع إجراء مقارنة توضح توقعات فعالية البديل المقترح مقارنة بالوضع الحالي .

لهذا الغرض تم معايرة واستخدام نماذج "Parametric Allocation" "Site Evaluation" كقاعدة تحليلية وبالتالي التركيز على متطلبات وقيود ونتائج العمل بهذه النماذج لتحليل الوضع القائم واقتراح التطبيقات المستقبلية . إن اختيار النماذج ، رغم مشاكل جمع المعلومات ، أظهرت أن الزيادة الجزئية في عدد المحطات ينتج عنه تحسينات ذات مغزي كبير في مستوى وقت الرحلة لخدمات الطوارئ وأن المنهج الذي استعمل يمكنه المساعدة في وضع استراتيجية ذات فعالية جازمة فيما يتعلق بتخصيص خدمات الإطفاء .