NBS TECHNICAL NOTE 782

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Application of Systems Analysis to the Operation of a Fire Department

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Application of Systems Analysis to the Operation of a Fire Department

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AN APPLICATION OF SYSTEMS ANALYSIS TO THE OPERATION OF A FIRE DEPARTMENT

Ernst K. Nilsson*
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Marilyn Westfall

Rising labor costs and increasing competition for tax dollars to provide urban services demand that a more precise methodology be used in the management of fire departments. A pilot program was conducted with the cooperation of the Alexandria, Virginia Fire Department to evaluate the applicability and usefulness of selected Operations Research tools. These tools, in the form of computer models, were modified and adapted to assure that they could be implemented to provide information which would facilitate fire department management. In this effort queueing, facility location, and simulation models were applied to sample data extracted from the historical records of the Alexandria Fire Department. It was established that such models do provide valuable information which may assist managerial decisions. This paper describes the city of Alexandria and its fire department, the O.R. models, output from their application, and evaluations of the output.

Key words: Alexandria; fire department; location; operations research; resource allocation; simulation; systems analysis.

1.0 INTRODUCTION

1.1 Purpose of Paper

This paper documents the application of Operations Research management tools to decision problems arising in the planning and provision of fire department services. The purpose of the paper is to demonstrate the utility of such an approach to city managers, planners, fire service officials, and other personnel unaccustomed to O.R. methodology. Therefore, an attempt has been made to exclude highly technical expositions. Instead, references are given to individual reports published by the Technical Analysis Division (TAD) of the National Bureau of Standards (NBS) which detail the mathematical procedures employed in the various models.

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1.2 Scope of Paper

This paper is based on a study done with the assistance of the Alexandria, Virginia Fire Department. Sections are included on each of the three major methodologies that were developed. The paper should be regarded as a practical demonstration that quantitative analysis can be useful to city and fire department decision makers.

1.3 Project Initiation

The Technical Analysis Division of the National Bureau of Standards was funded in June 1970 by the Office of Fire Research and Safety to demonstrate the applicability of Systems Analysis and Operations Research techniques to fire service problems. TAD contacted the Alexandria Fire Department for permission to use their actual engine and truck company reporting forms for the period of May through August, 1970. The fire department was also requested to identify local problems for solution. The major question posed by the Alexandria Fire Department concerned the probable effects of proposed changes in their pattern of fire station locations.

1.4 Operations Research

Operations Research (O.R.) developed in response to the increasing need for efficient and scientific methods to study problems involving the interaction among various operational units within more complex, organizations. The field employs scientific methods, techniques, and structures to analyze problems involving the operations of a system of activities so as to delineate for management alternative choices of action or decision. O.R. has evolved a methodology drawn from the appropriate aspects of mathematics, social science, and the physical sciences to provide problem solving techniques for problems of an operational nature. The general procedure is to:

1. Study the objectives of a system and determine the essential factors - the cause-effect relationships - involved in its operations,
2. Determine and implement a way to measure the essential factors and collect the pertinent data,
3. Construct a model to represent the system under study,
4. Derive various practical solutions from the model,
5. Test the methodology and the solutions derived from its use,
6. Use the solutions to suggest courses of action which will further the goals of the system [1].[1]

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[1] Figures in brackets indicate the literature references at the end of this paper.

This study applies the above methodology, using several different types of mathematical models. The specific applications will be discussed in detail in later sections.

Section 2 describes the city of Alexandria and the particulars of its fire department. Section 3 discusses the data which was collected and how it was tabulated. Sections 4, 5, and 6 apply different methods of analysis to the data to answer specific questions. Section 7 is a brief summary of the paper.

2.0 ALEXANDRIA, VIRGINIA

2.1 City Background

The city of Alexandria, Virginia covers an area of 15.3 square miles, and listed a population of 110,938 persons in the 1970 census. The population increased by 19,915 persons from the 1960 figure, but the increase was appreciably smaller than that of the preceding years:

Census Year	Population	Increase from Previous Census
1950	61,787	29,264
1960	91,023	29,236
1970	110,938	19,915

The distribution of the population by census tract is presented in Figure 1.[2]

Alexandria is the site of the largest railway switching stations on the Eastern Seaboard; Potomac Yards covers 520 acres. The Port of Alexandria has a busy traffic in newsprint and stock for the many import and specialty shops in the area. Because the city is so heavily residential, there is little space for large and heavy industry. However, there are many smaller manufacturers producing such items as pre-cast concrete, chemicals, fertilizers, mattresses, flags, and foundry castings.

Over 30 percent of the total work force is employed by the federal government in nearby Washington, D. C., and many more work for firms holding government contracts. The cash income level of the inhabitants ranges as follows:

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[2] In future planning studies, projections of population growth will be needed in order to base station locations on anticipated demands for service.

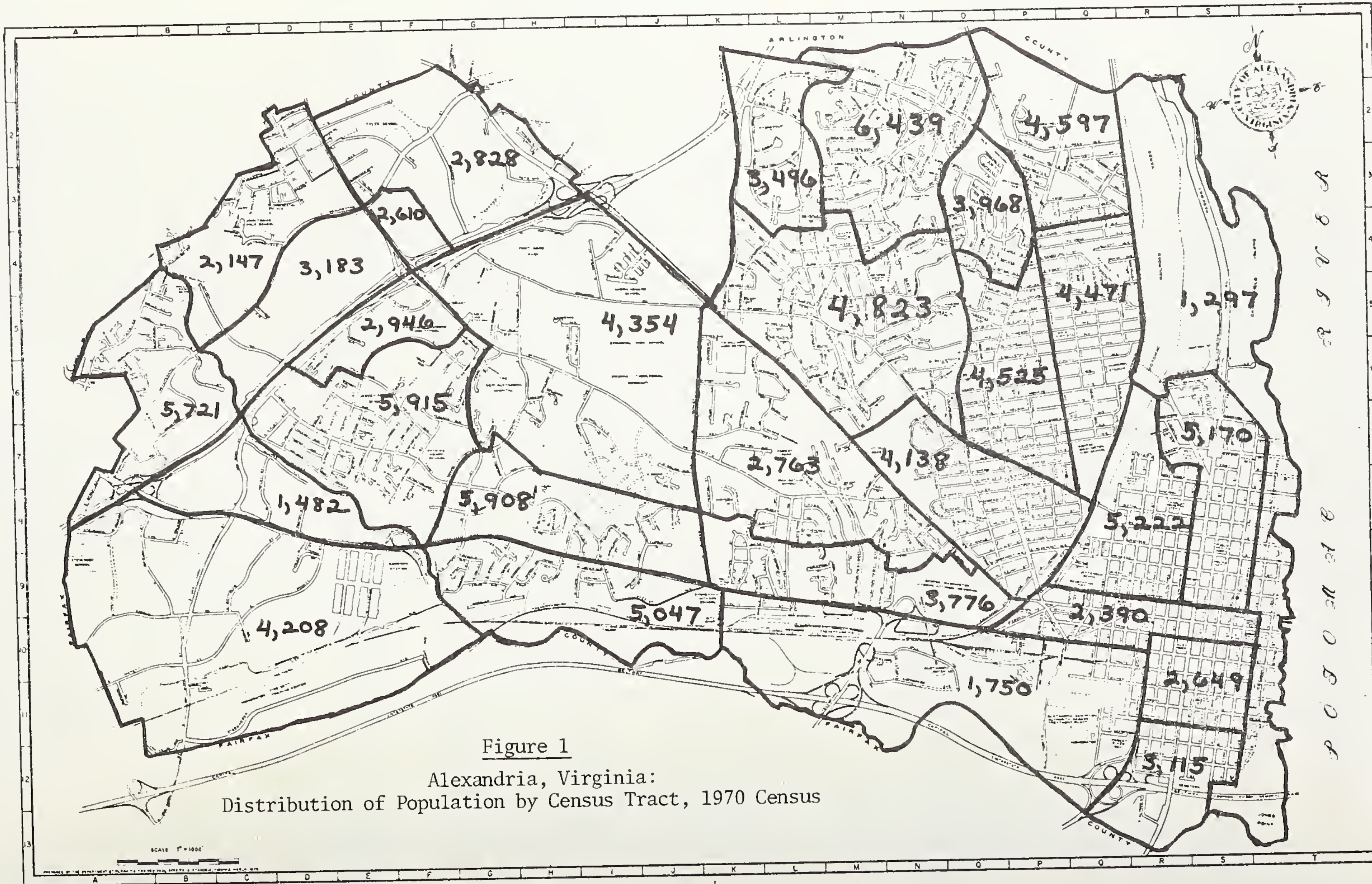


Figure 1

Alexandria, Virginia:
Distribution of Population by Census Tract, 1970 Census

Family Income	Percentage of Population
$0-2,999	9.2%
$3,000-4,999	10.1%
$5,000-7,999	23.6%
$8,000-9,999	15.8%
$10,000-over	41.3%

Alexandria has a total of 44,426 housing units, approximately 1,950 of which are vacant. Almost half of the occupied units consist of 29,750 garden apartments, which have become the predominant type of housing in the last ten years. In addition to 16,000 family homes, there are 8,884 high rise units, 90 percent of which were constructed in the last decade. Considerable redevelopment has been completed in the older eastern portion of the city. In the western sector, new housing projects have been initiated. The Alexandria Redevelopment and Housing Authority administrates 1,034 public housing units which house a total of 4,075 inhabitants.

Alexandrians are acutely aware of the historical significance of their city, one of the earliest towns to be incorporated after the American Revolution. Careful preservation and restoration of historical sites receives great emphasis in city planning.

2.2 Organization of the Fire Department

The Alexandria Fire Department is funded by local city taxes. During the 1970 fiscal year, the city's fire protection services cost the average family of four approximately 25 cents per day in taxes. Expenditures by the fire services for the same time period totaled $4,984,600. This amount was budgeted for:

Category	Amount in Dollars
personnel services	2,294,990
non-personnel services	109,885
capital outlay	88,520
administration	104,595
firefighting	1,786,345
fire prevention	143,830
rescue	169,795
maintenance	113,390
communications	129,635
training	43,615

Alexandria's fire department engages 184 employees, all of whom are salaried personnel. They are assigned to the following permanent duties:

Duty	Number of Employees
administration	7
firefighting	136
fire prevention	11
rescue squad	12
maintenance	7
communications	8
training	3

The fire department system is comprised of seven fire stations. Each station houses one engine company composed of one or two pumpers with a complement of five men each. Their major function is the attack of fire with water. The engine companies at stations 2, 4, 5, and 6 consist of two pumpers, and those at stations 1, 3, and 7 consist of one pumper. The system also includes four truck companies, each of which consists of one truck and a complement of five to seven men. Their functions include raising ladders, ventilation, salvage, overhaul, and rescue work. There are also two rescue squads each consisting of three ambulances of which two are in service and one in reserve. The locations of these units are shown in Figure 2.

The fire department responds to emergencies and carries on various other appropriate activities.

2.3 Emergencies

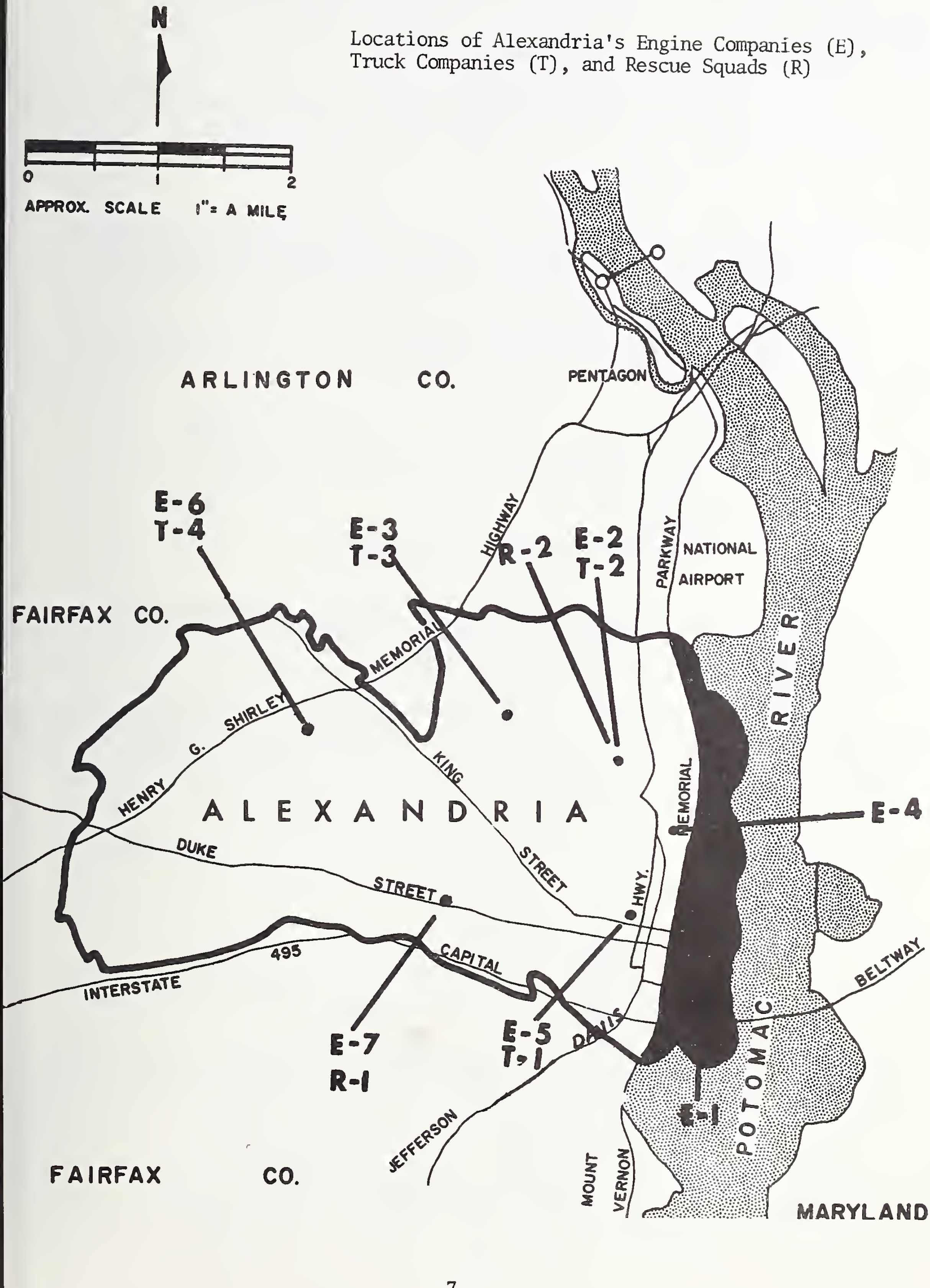
The fire department received a total of 2,693 alarms in 1970 which were classified in the following manner:

Actual Fires	
in buildings	703
brush, grass, woods	258
trash and litter	138
miscellaneous outdoor fires	112
vehicles on streets	1539

Other Alarms	
accidental	86
public service	481
false	553
fires out of city	34

Figure 2

Locations of Alexandria's Engine Companies (E), Truck Companies (T), and Rescue Squads (R)



The rescue squad responded to a total of 6,958 emergencies. The general procedure is to transport all victims to Alexandria Hospital on Duke Street, and then if necessary to transfer them to a hospital which can treat their specialized ailment or injury.

The fire department also participates on a standby basis in riot control.

2.4 Other Activities

The fire department is responsible for its own cooking, housekeeping, building maintenance, and equipment repair. In 1970, 6,000 hours of training sessions were conducted occupying 21,500 man hours.

During 1970 the fire department conducted a total of 7,836 fire safety inspections of the following premises:

public buildings	432
dwelling occupancies	3385
mercantiles (warehouses, offices, stores, restaurants)	2325
manufacturing	391
miscellaneous buildings (railroads, wharf property, oil storage, etc.)	1303

In May of each year, Fire Service Day is held to acquaint citizens with their fire service and its role in the community, through talks, open houses, and tours through the fire stations.

An annual fire prevention week program promotes fire prevention courses and regular drills in public schools, the elimination or protection of sub-standard buildings, the installation and checking of sprinkler alarm systems and first aid equipment in industrial and mercantile buildings, and clear marking of exits in public buildings.

A miscellaneous assortment of community services are continually provided, including:

- replacing flagpole ropes
- rescuing stranded children and animals
- collecting muscular dystrophy funds
- giving lectures, demonstrations, and film presentations on fire hazards
- conducting practice evacuations in hospitals, nursing homes, and commercial establishments
- handling complaints
- checking foster homes.

3.0 DATA COLLECTION AND TABULATION

A total of 123 days of data was collected covering each engine and truck company response during May, June, July, and August, 1970. The data was taken off the company report form (see Figure 3) which is filled out by each truck and engine company responding to an alarm. TAD personnel transferred the data items to the computer compatible data form shown in Figure 4.

As the data sample was limited to four months, any conclusions pertain strictly to that limited time period. However, the data analysis is illustrative of possible procedures.

Once the forms had been completed, the information was reviewed and certain factors were tabulated, including the distribution of calls for service by:

A. Time of day
B. Type of call
C. Service times and resource utilization
D. Location.

3.1 Calls for Service by Time of Day

The calls for service (CFS) were distributed by time of day as shown in Figure 5. A marked increase in demand during the evening hours is visible. The variation in frequency of calls is highlighted by dividing the day into the three time periods used in Table 1A. This breakdown shows twice as many CFS during Period III as during Period I. Other temporal divisions are possible, as in Table 1B. The difference in demand load is still evident.

For the 123 day period, the average number of calls per day was 7.73. The average per period was:

Time Period	Average Number of Calls for Service
0001-0800	1.47
0800-1600	2.44
1600-2400	3.82
	7.73

This information suggests that if there is a temporary manpower shortage, it might be desirable to ensure sufficient personnel for the third period rather than to assign equal numbers of employees for each period. If such averages were computed by company for a larger sample, preferably a complete year, they could be used to compare work loads and adjust personnel assignments for the individual companies. Seasonal changes in these norms could be used to determine the establishment of leave periods and policies.

Figure 3

F.D. FORM 6
6M—4-50

CITY OF ALEXANDRIA, VIRGINIA
FIRE DEPARTMENT

Company ____________

Monthly Number ____________
Annual Number ____________
Date ____________

Location of Alarm ____________
Type of Alarm ____________ Time of Alarm ____________ Time in Service ____________
Source of Alarm ____________ Received by ____________
Number of Stories in Building ____________ Construction of Building ____________
Occupancy of Building ____________ Location of Fire ____________
Origin of Fire ____________
Owner of Building, Property or Vehicle ____________
Occupant or Tag of Vehicle ____________
Insured ______ Uninsured ______ Agent ____________
Amount Insurance Property ____________ Amount Insurance Contents ____________
Was There Damage to Property? ____________ Damage to Contents? ____________
Was Pump Operated? ______ Time Operated ______ Size Pump ____________
Was Booster Used? ______ Time Operated ____________
Hydrant Stream Used? ______ Time Used ______ Location and Condition of Hydrant ____________
Size and Feet of Hose Line Used: 3 inch ____________ 2½ inch ____________
1½ inch ____________ Booster ____________
Apparatus Answering Alarm ____________
Drivers ____________
Number of Men Responding ______ Number of Men Injured ______ Number Killed ______
Name and Nature of Injury ____________

Type and Number of Extinguishers Used ____________
Salvage Covers Used ______ Left at Scene ______ Other Tools Used ____________

Feet of Ladders Used: ______ Single ______ Extension ______ Aerial ______
Damage/Loss of Equipment: ____________
Damage to Apparatus: ____________
Citizens Injured by Fire ____________
Citizens Killed by Fire ____________
Department Officer in Charge ____________
Company Officer in Charge ____________
Tract ______ Remarks ____________

10

Signed ____________
Title ____________

Figure 4

FIRE STUDY
[TAD Form]

1. Annual No. ___ ___ ___ ___ (1 2 3 4)

2. Address: ___ ___ ___ ___ (5 6 7 8)

3. Type of alarm: ___ (9)

1 = Public Service
2 = Special
3 = Malicious alarm
4 = Accidental alarm
5 = No fire
6 = Fire
7 = Mutual Aid Assignment

4. Units responding:

engine = 1 or 2
truck = 3

	Unit	Time Out	Time In	Pump Op. (min)	No. of Men
a.	10	11 – 14	15 – 18	19 20	21
b.	22	23 – 26	27 – 30	31 32	33
c.	34	35 – 38	39 – 42	43 44	45
d.	46	47 – 50	51 – 54	55 56	57
e.	58	59 – 62	63 – 66		67
f.	68	69 – 72	73 – 76		77

5. Date:

___ ___ (78 79) day

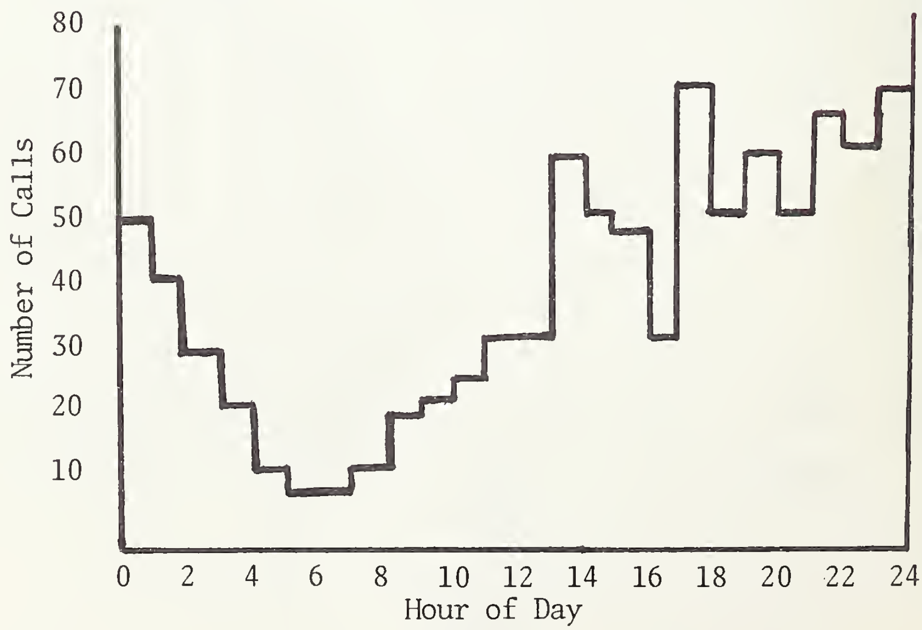
___ (80) month

Figure 5

Distribution of Calls by Hour of Day

During a 123 Day Period

Hour	Number of Calls Occurring in Hour	Fraction of Total Number of Calls	Hour	Number of Calls Occurring in Hour	Fraction of Total Number of Calls
1	50	0.052	13	36	0.038
2	38	0.040	14	59	0.061
3	30	0.031	15	50	0.052
4	24	0.025	16	48	0.050
5	13	0.014	17	33	0.034
6	7	0.007	18	73	0.076
7	8	0.008	19	50	0.052
8	15	0.016	20	63	0.066
9	22	0.023	21	49	0.051
10	24	0.025	22	70	0.073
11	29	0.030	23	62	0.065
12	36	0.038	24	72	0.075



Frequency of Calls for Service by Eight Hour Periods for 123 Days of Calls

Table 1.A.

First Breakdown

Period	Time Period	Frequency of Calls	Percent of Total Calls
I	0001 - 0800	185	19.3
II	0801 - 1600	304	31.6
III	1601 - 2400	472	49.1
		961	100.0

Table 1.B.

Second Breakdown

Period	Time Period	Frequency of Calls	Percent of Total Calls
I	0101 - 0900	157	16.3
II	0901 - 1700	315	32.8
III	1701 - 0100	489	50.9
		961	100.0

Statistical tests were also conducted to examine variations in the number of calls for service by day of the week, but no statistically significant difference was found. This is an unusual finding since such differences were found for data collected by NBS for other cities.

It was not appropriate to tabulate the distribution of service calls by month of the year because of the limited sample.

3.2 Calls for Service by Type

The calls for service were divided into three types:

1. Public Service and Special Services

   Public service calls involve a non-fire and non-hazard related service such as replacing a flagpole rope or rescuing a cat in a tree. If a hazard exists which the fire department is specifically equipped to handle, such as draining a water-filled basement or washing down a street after an accident, the call is designated as a special service call.

2. False Alarms

   If an alarm is given with malicious intent when there is no actual fire,[3] the call is considered a false alarm.

3. Suspected Fires, Real Fires, and Accidental Alarms

   A suspected fire is an alarm given with good intent because the caller mistakenly assumed a fire from such signs as smoke from a stove grease fire or burnt bearings in a furnace fan. A real fire consists of smoke and flames. An accidental alarm occurs due to such mechanical malfunctions as a water surge in an automatic sprinkler system.

The average number of calls for service per day by type during the three time periods was tabulated and is shown in Table 2.

Table 3 shows the distribution of the number of days having a given number of calls for service of the various types. For example, there were 24 days during the 123 day period when two Public Service calls occurred. There were five days when there were zero calls for service. This information is presented graphically in Figure 6.

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[3]An alarm is considered to have been given with malicious intent when no fire is found and the caller has left the scene.

Table 2

Average Number of Calls for Service per Day
by Type and Time Period

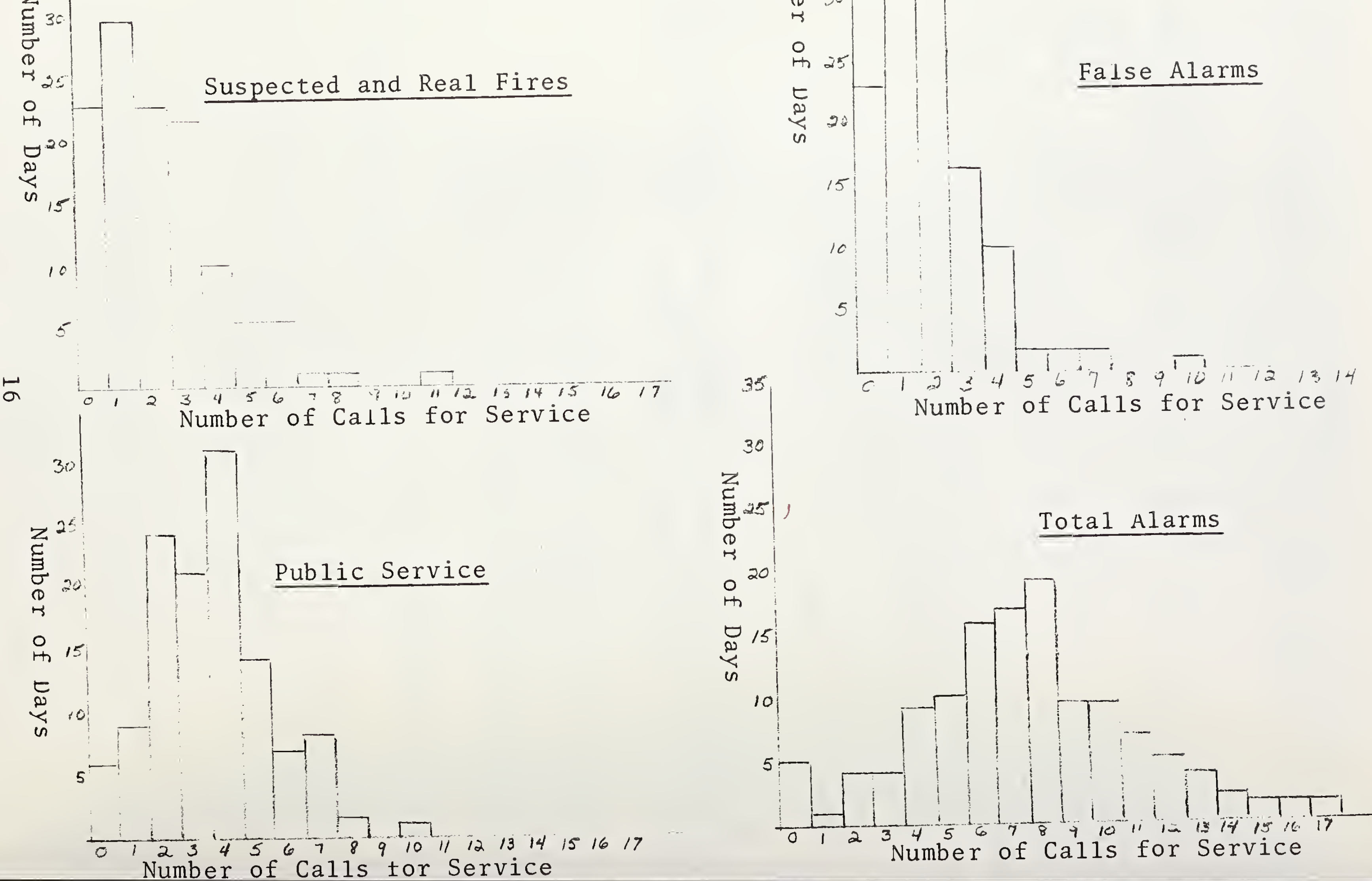
Type/Time Period	0001 - 0800	0800 - 1600	1600 - 2400	Total
Public Service	.49	1.35	1.76	3.60
False Alarms	.54	.33	1.04	1.91
Suspected and Real Fires	.44	.76	1.02	2.22
Total	1.47	2.44	3.82	7.73

Table 3

Number of Days Having a Specified Number of Calls for Service

Number of Calls for Service Per Day (N)	Number of Days Having (N) Public Service Calls	Number of Days Having (N) False Alarms	Number of Days Having (N) Real Fire Calls	Number of Days Having (N) Total Calls
0	6	23	23	5
1	8	34	30	1
2	24	32	23	4
3	22	17	22	4
4	31	10	10	9
5	14	2	6	10
6	7	2	6	16
7	8	2	1	17
8	2	0	1	19
9	0	0	0	9
10	1	1	0	9
11	0	0	1	7
12			0	5
13				3
14				2
15				1
16				1
17				1

Figure 6
Distribution of Calls by
Type of Call



3.3 Calls for Service by Service Time

Service time is defined as the total time that a company devotes to an alarm. This includes travel time to the scene, time spent handling the alarm, and return travel time.

The concept of service time is useful since knowledge of average service time by type of call provides a quantification of the different demands on company time. In addition, both the average number of calls per day and the service times are needed for the analysis in Section 4. Table 4 shows the average service time for the various types of calls; Table 5 shows the frequency distribution of service times for all calls.

Engine and truck companies are defined here as the resources available to handle alarms. An important factor is the amount of time that these resources spend handling alarms. Table 6 shows the number of calls handled by each company, as well as the number of minutes each company spent handling calls during the 123 day period. The last column in the table was derived in the following manner. The number of minutes from the previous column was divided by the total number of minutes in the 123 day period (i.e., 123 days x 24 hours x 60 minutes=177,120 minutes). The result is the percentage of work time spent actually handling alarms. These percentages are averages for the total 123 days.

3.4 Calls for Service by Location

Figure 7 shows the geographic distribution of calls for service in Alexandria, Virginia on a grid of 1500 foot square cells. It is evident that the calls over the 123 day period tend to cluster. This clustering has possible implications for fire station location, assignment, and unit relocation policies. The distribution by location of false alarms throughout the city is shown in Figure 8. The geographic distribution of calls for service could be further specified by time period and/or by type of call. Changes in patterns of alarms could then be correlated to demographic or seasonal changes to provide information useful for suggesting or evaluating such proposed new procedures as tactics to reduce false alarms.

There are indications that the incidence of fire alarms is associated with the socio-economic characteristics of different areas of the city. For example, the New York City Rand Institute [2] has found a high correlation between fire department and police department calls for service, with respect both to time of occurrence and to location.

Table 4

Average Service Time (in minutes) by Type of Alarm

Type	Average Service Time in Minutes	Number of Calls in 123 Days
Public Service	22.12	249
Special Services	24.84	191
False Alarms	9.59	241
Accidental Alarms*	80.16	19
Suspected Fires (smoke, etc.)	18.72	137
Real Fires	33.16	124
Total		961

Table 5

Frequency Distribution of Service Times
For All Calls (in five minute intervals)

Minutes	Number of Calls	Percent of Calls
0 - 5	23	2
5 - 10	198	21
10 - 15	216	23
15 - 20	153	16
20 - 25	96	10
25 - 30	56	6
30 - 35	47	5
35 - 40	48	4
40 - 45	20	2
45 - 50	13	1
50 - 55	18	2
55 - 60	7	1
60 - 65	7	1
65 - 70	16	2
70 - 75	7	1
75 - 80	5	1
$\geq$ 80	22	2
	952**	100%

Mean = 22.10 minutes
Standard Deviation = 17.58

---

* The long average service times for accidental alarms occur because the fire department must wait for the representative of the alarm company, determine that there is no fire, and find the cause of the automatic system malfunction.

** Nine cases were not included because of insufficient data.

Table 6

Number of Calls and Time Out of Station by Company

Engine Co.	Number of Calls	Minutes Spent Handling Alarms	Resource Utilization
1	147	3806	2.2%
2	137	4635	2.6
3	123	3617	2.0
4	228	5013	2.8
5	221	8192	4.6
6	133	3042	1.72
7	130	3827	2.17
		average	2.6%

Truck Co.	Number of Calls	Minutes Spent Handling Alarms	Resource Utilization
1	143	3622	2.0%
2	82	2319	1.3
3	74	2184	1.2
4	76	2085	1.8
		average	1.6%

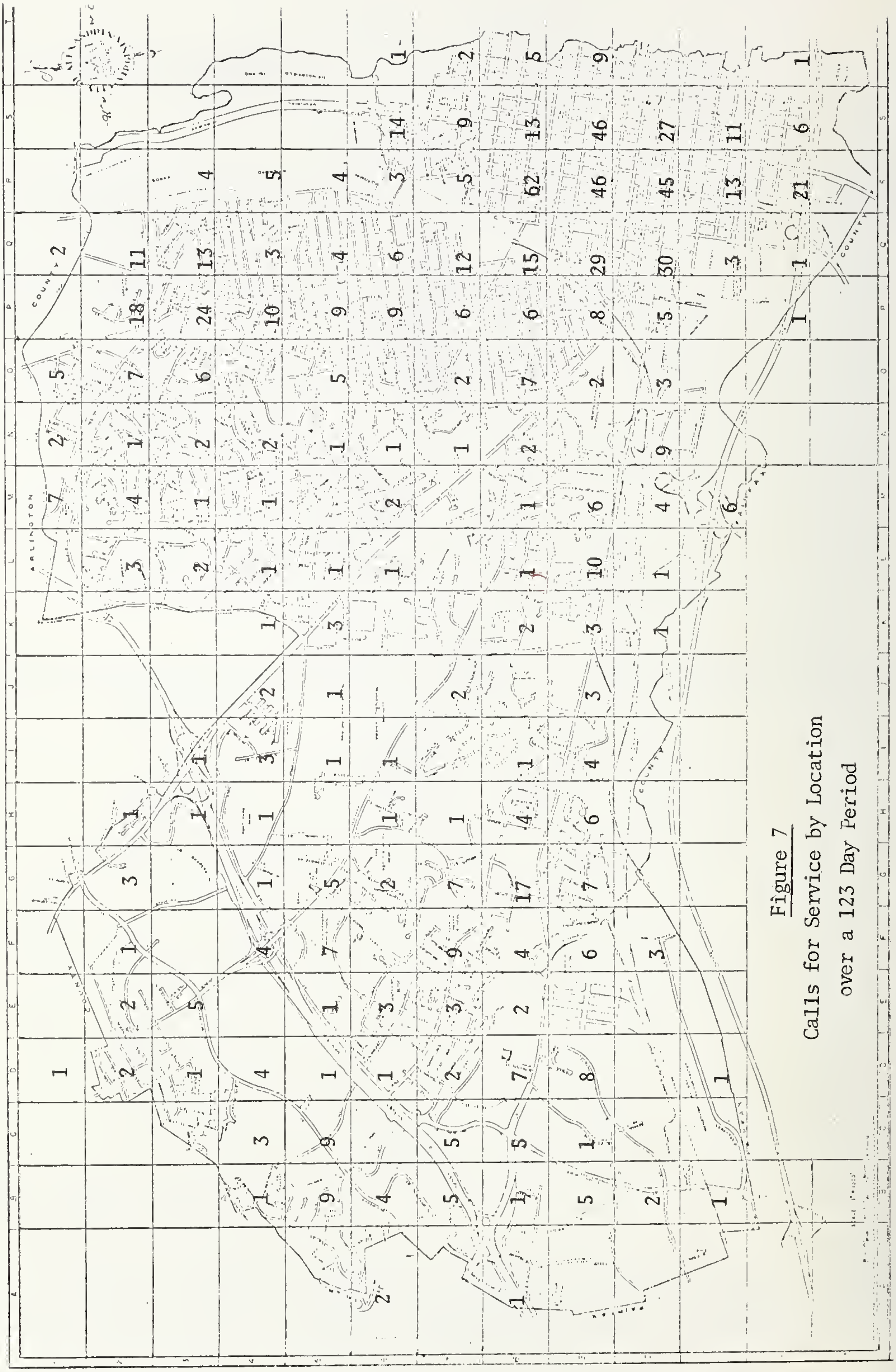


Figure 7
Calls for Service by Location
over a 123 Day Period

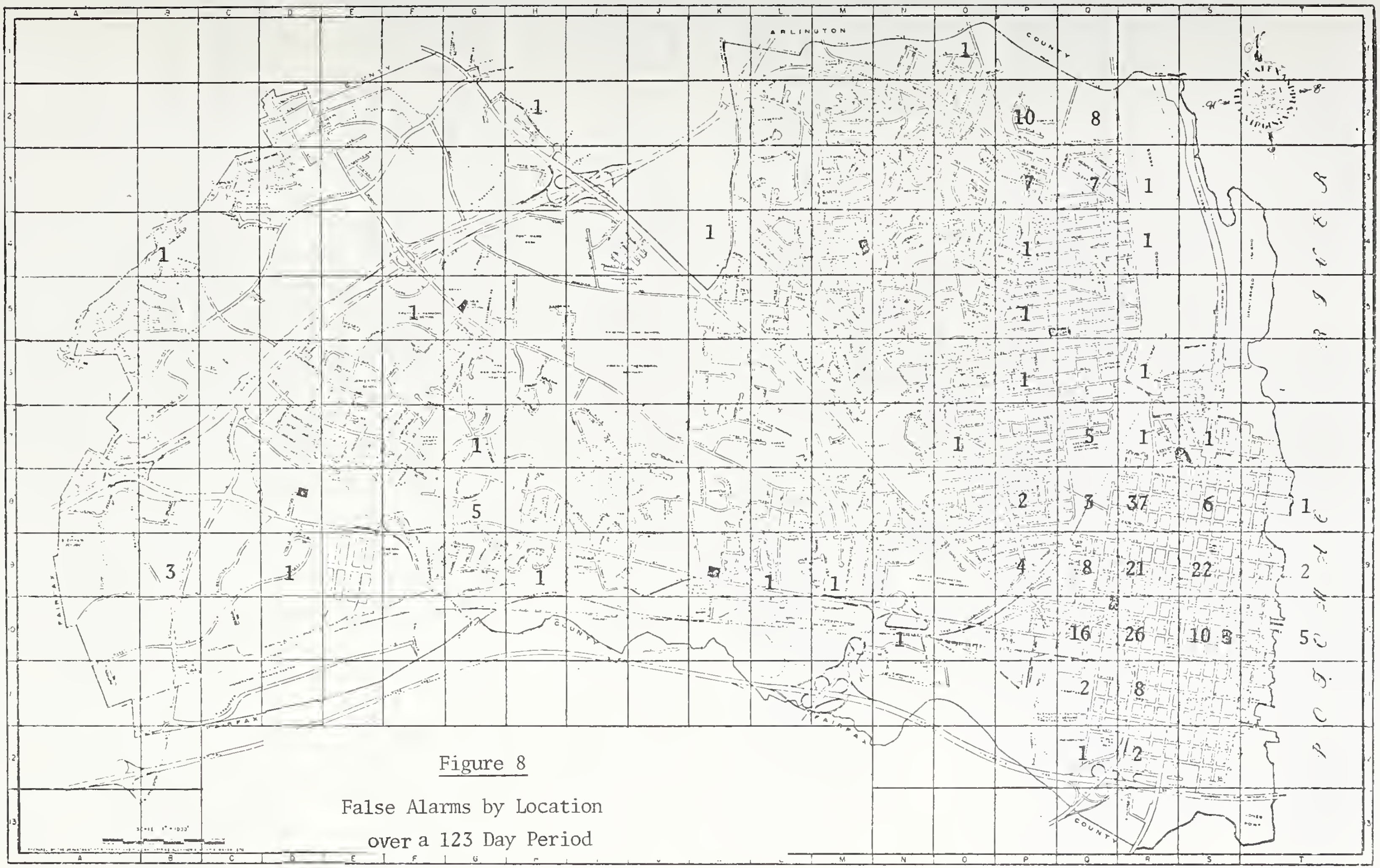


Figure 8

False Alarms by Location
over a 123 Day Period

Data displays, like those shown in this section, are useful for developing an intuitive understanding of the demand for services and the resource utilization in a fire department, and for determining the origin locations of alarms of different types.

Where and when demands for service occur evidently has implications for the number of resources needed and their proper locations. However, further analysis is necessary in order to answer these two questions.

Section 4.0 utilizes Queueing theory to analyze the temporal aspects of demands for service. Section 5.0 implements concepts of Location theory to generate and assess various fire station location patterns. The alternatives provided by Sections 4.0 and 5.0 are then evaluated in Section 6.0, using a simulation model capable of combining both temporal and spatial aspects.

4.0 APPLICATION OF QUEUEING THEORY

Analysis of a resource allocation problem often involves determining the necessary number of resources required to handle demands for a specific service when the demands arise randomly. Such demands might originate from supermarket customers at check-out counters, phone calls at a switchboard, or citizens requiring police or fire service. The common element is that there are identifiable demands for service which occur randomly.

Queueing theory - so called because it concerns the properties of waiting-lines or "queues" - is a mathematical tool which is useful in the consideration of such questions. It provides means for characterizing the rate at which demands arise, the rate at which service is provided, and the effect of both rates on the ability of the system to respond.

For instance, customers in a supermarket having only one check-out counter may have to wait in line so long that they become impatient and leave the store. Management can furnish additional counters to relieve the delay in service, but there is a fixed cost associated with each manned counter in terms of construction and salaries. Some balance must be established between increased cost and customer inconvenience.

4.1 Availability Analysis

The adaptation of Queueing theory to the fire services is primarily concerned with insuring that "enough" resources will be available when needed. "Enough" is a policy variable that the local jurisdiction must determine in accord with its economic and political situation.

Queueing theory provides estimates of resource utilization, the probability of an alarm having to wait before being served, and the probable length of the wait. This type of analysis, applied to fire services, will be referred to as Availability analysis. Fire alarms represent demands for service, and the number of engine and truck companies constitute the resources.

Availability analysis provides a fire chief with such specific information as: "the incidence of a citizen calling for aid when no equipment is available to provide service will (on the average) occur once in four years with seven companies, and one in forty years with eight companies." He may then calculate the costs of providing the two different levels of protection (seven or eight companies), and the average and maximum times callers may expect to wait for an emergency vehicle in each instance. Such data, together with a "per company" cost figure, would inform the citizens as to how much they would have to pay for a specific capability of this vital urban service.

4.2 Assumptions

Availability analysis makes certain assumptions about the behavior of demands for service and the time it takes to service them [3]. As applied here, it assumes that the times at which demands arise can be modeled mathematically using a "Poisson distribution". This implies that the individual calls for service occur randomly, that the times at which they arise are independent of the pattern of arrivals of previous calls, that there is no periodicity in the pattern of calls, and that the probability of two or more calls arriving within a very short time interval is essentially zero.

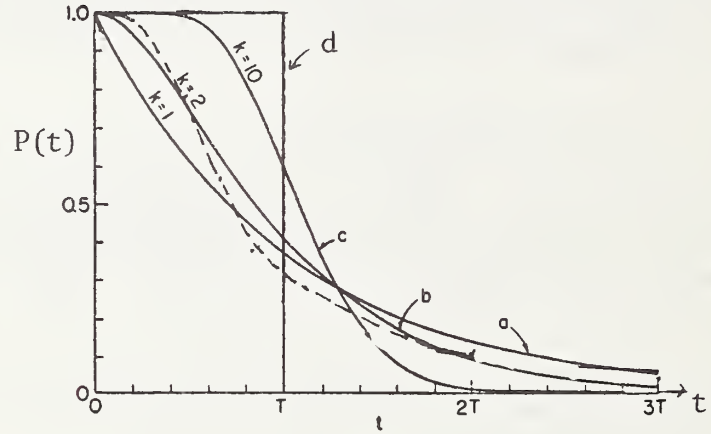
This assumption of Poisson distribution of calls for service was tested for the 123 days of historical data collected in Alexandria. Although the rate of arrival of the calls, was assumed to be constant during average periods of the day, this rate changes, from period to period, with peaks and valleys in the data. The hypothesis was that the distribution of actual arrival times of calls for service to the Alexandria Fire Department during each period was the same as the mathematically predicted distribution except for reasonably likely chance variations. A standard statistical (Chi-Square) test was employed to test the acceptability of this hypothesis, and it was ascertained that the hypothesis could not be rejected at the 1% level of significance. Therefore, the assumption of Poisson arrival rates was accepted as consistent with the data.

At first the additional hypothesis was made that service times follow a "negative exponential" distribution. This implies that each service time has a constant probability of termination in the next small increment of time, regardless of how long service has already been in progress. One characteristic of this distribution is that the mean is equal to the standard deviation. For the Alexandria data, the service time distribution had a mean of 22.10 minutes and a standard deviation of 17.58 minutes. A Chi-Square test was again used, this time to test the hypothesis that the empirical service time distribution was negative exponential. This hypothesis had to be rejected at the 1% level of significance. The next simplest "standard" probability laws for service times (Erlang distributions for k = 2, and 10) were also tried, but had to be rejected at the 1% level of significance.

Figure 10 shows the negative exponential, Erlang and constant service time distributions. The vertical axis is the probability, P(t), of a service time being greater than t. The horizontal axis is time (t) measured in average service units (T).

Figure 9

Service Time Distributions



a = Negative exponential distribution (k = 1)
b = Erlang distribution for k = 2
c = Erlang distribution for k = 10
d = Constant service time distribution

The dotted line represents the actual time distribution from the Alexandria data. It is evident that there are fewer short and very long service times in comparison to the negative exponential distribution.

This means that the actual service time distribution is more regular than the negative exponential distribution, though, of course, less so than the constant (i.e., "completely regular") service time distribution. Therefore, if the negative exponential distribution were used to estimate the behavior of the system, it would overestimate the expected queue length, the probability of a wait in queue, etc. It is useful to have an analytical method to obtain approximations to measures of the performance of a system, and the negative exponential distribution was used here to estimate upper bounds for such measures. For example, the actual average queue lengths and the probability of a wait before a call can be handled will always be less than those predicted by the model.

4.3 Application

Availability analysis was applied to the sample data collected in Alexandria.

The questions to be answered were:

1. How many companies are needed?
2. What percentage of their total time is spent answering alarms?
3. What is the chance of a given number of alarms occurring per hour?
4. What is the chance that there will be no equipment available for assignment when an alarm occurs?
5. What is the probability of having to service a given number of alarms simultaneously?

The Poisson distribution was applied, using the historical arrival rates (calls per hour) of calls for service. Since demands for service change as a function of the time of day, the days were divided into three time periods (0000-0800, 0800-1600, 1600-2400), to account for gross differences in the hourly level of demands for service. The average number of calls in each time period was then divided by the number of hours (8) in that time period to find the average arrival rate per hour. A peak load estimate was arrived at by determining how many calls during the 123 day period occurred during each hour of the day, then dividing the highest of these numbers of calls by the 123 total days. This resulted in a peak hour average of 1.08 calls per hour.

Table 7 shows the chance of receiving a given number of calls in any given hour, assuming the arrival rates thus determined. It is read as follows: If the average number of calls coming into the system is 3.82 during the 1600 to 2400 (4:00 p.m. - midnight) time period, there is a 62% chance that no alarms will be received during any specific hour in that time period.

The probability that a given number of companies will be unavailable for a call for service because they are handling prior calls was determined using a model developed by Jan Chaiken at the New York City Rand Institute.[4] Data from the third time period (1600 - 2400) was used to illustrate the effects of a higher level of demand.

First, the arrival rate of calls to which 1, 2, 3,...,n, engine companies were dispatched was tabulated. Next, the average time that there were X (X = 1, 2, ..., n) units at the scene was calculated. For example, when three companies were dispatched it was necessary to determine how long, on the average, there were three, two and one engine companies on the scene.

Table 7

Probability of n Number of Calls/Hour

for Different Time Periods

Time Period	Arrival Rate Calls/Hr.	n: 0	1	2	3	4	5	6	7
daily rate	7.73/24	.7246	.2334	.0376	.0040	.0003			
1600-2400	3.82/8	.6203	.2962	.0707	.0113	.0013	.0001		
0800-1600	2.44/8	.7371	.2248	.0343	.0035	.0003			
0000-1800	1.47/8	.8321	.1529	.0140	.0009	.0000			
peak hour load	1.08/1	.3396	.3668	.1981	.0713	.0193	.0042	.0007	.0001

The Chaiken model assumes negative exponential service times. In addition, it assumes that, for a given dispatch, the durations of successive stages of service are independent and that the number of units engaged decreases from stage to stage. A stage of service is defined as that period during which a particular number of units are engaged at the scene.

This model is very flexible and can be used to analyze changes in arrival rates, dispatch policies, and service times for different types of calls for service.

Table 8 shows the availability of engine companies in Alexandria during the 1600-2400 time period. The probability that six companies will be occupied at the same time during the eight hour period is 0.001, or once in 1,000 eight hour periods. In this instance, the probability that more than six companies will be occupied at the same time during an eight hour period is also 0.001, or once in 1,000 eight hour periods.

Another measure of interest is the probability that there will be some delay before an adequate response unit can be assigned to a call for service. Queueing analysis provides this measure in terms of the number of "servers" available. A fire department dispatches different numbers of engine companies to different types of calls. The dispatch policy varies, for example, according to whether the department has been asked to pump out a basement or to respond to a fire alarm. During the 123 day period the maximum number of engines dispatched for any single call was three. Taking a conservative position, it was assumed that three engine companies were dispatched to all calls for service. In queueing theory parlance, this is equivalent to making the three engine company dispatch equal to a server. Then:

(1) The probability that sufficient engine companies are not available when an alarm occurs is (using third shift data):

For 6 Companies (2 servers)	For 9 Companies (3 servers)
0.0107	0.0005

In other words, if the fire department had six engine companies and always responded with three companies to each alarm, some delay in response would be expected, given the arrival and service rates for the 1600-2400 time period, roughly one time out of 100 alarms; i.e., 100 times out of 10,000 alarms. If there were nine engine companies, some delay would be experienced only five times out of 10,000 alarms.

Table 8

Theoretical Model of Availability During

the 1600-2400 Period for Alexandria

N	Probability of (N) Companies Busy	Probability of the Number of Companies Busy Being Greater than (N)
0	.809	.191
1	.107	.084
2	.031	.053
3	.043	.010
4	.006	.004
5	.002	.002
6	.001	.001
7	.0002	.0008
8	.0001	.0007

(2) The probability that there will be a specific delay before enough companies become available is:

Probability of Waiting Time Greater Than (T) Minutes; Third Shift Data

Time (T) Min.	6 Co.	9 Co.
10.0	.0064	.0003
9.0	.0068	.0003
8.0	.0071	.0003
7.0	.0075	.0004
6.0	.0078	.0004
5.0	.0082	.0004
4.0	.0086	.0004
3.0	.0091	.0004
2.0	.0095	.0005
1.0	.0100	.0005
.5	.0102	.0005
.25	.0104	.0005

In each time interval, the chance that response to a call for service will be delayed when there are six engine companies is more than ten times as great as the chance when there are nine engine companies.

(3) The fraction of time that the companies will be servicing calls is:

6 Co.	9 Co.
2.5%	1.7%

The actual utilization factor of 2.6% for the Alexandria Fire Department's present seven companies agrees well with the numbers predicted by the model.

5.0 APPLICATION OF LOCATION MODELS

If unlimited funds were available to supply resources, the Fire Department could theoretically maintain individual stations to protect each city block. However, since public service facilities are constrained by budget provisions, it is necessary to assign the available resources to the best strategic locations to ensure maximum effectiveness. Location analysis can be applied to this spatial aspect of fire service problems.

Because response time is an integral factor in saving lives and reducing property loss, "the objective function" or goal of various location models is to reduce the time required to reach all demands for service by the nearest resource to each call. Since building-by-building or block-by-block identification would yield an excessive number of data items for the types of computation required, the area under study is divided into "zones", and response times are calculated from the nearest fire station to the zone. By comparing the various response times from actual and potential station locations, it is possible to evaluate the relative efficiency of different configurations of station locations. The function of a location model is to determine the "optimum" locational pattern, where the optimum is defined as the configuration yielding the minimum average response times.

Two types of location analyses were used to generate and evaluate alternatives: an adaption of the Maranzana transportation algorithm [5] and a modification of the REDIST algorithm used to determine voting districts [6].

Both location methods use a heuristic (i.e., a decision-rule that doesn't guarantee a precisely optimal solution) to determine a "good" solution at reasonable computer cost. The locational patterns generated by the Maranzana and REDIST methods were used as two additional alternatives to be compared with alternatives suggested by the Alexandria Fire Department through the use of a simulation method to be described in the next chapter.

5.1 Assumptions

Several assumptions (the first three of which reflect normal fire service operating procedures) were made in applying the Maranzana and REDIST models:

1. The important response time is that of the first due engine company, and it is that response time which should be minimized.

2. Each engine company is assigned to one station at a fixed location. The company always responds <u>from</u> the station, and is assumed to be <u>in</u> its station when not servicing calls.

3. A given fire demand zone is served exclusively by the closest engine company.

4. All alarms occurring within a zone are treated as occurring at the center of that zone.

5. Travel times from zone centers to each potential station location are known.

A simplified method was used to determine the zones and travel times in Alexandria. The steps were as follows:

1. Zones were equated with the 1500 x 1500 feet cell divisions mentioned in Section 3.4.

2. Calls for service within a cell were assumed to originate at the center of that cell.

3. An (x,y) coordinates system was developed with coordinates (0,0) at the northwest corner (see Figure 11). For example, the midpoint of the shaded cell has coordinates (0.5, 0.5).

4. The existing fire stations were placed on this coordinate system as the initial set of locations for the model to improve upon.

5. The distances between existing and proposed fire station locations and the centers of the cells were measured along theoretical streets paralleling the coordinate grid.

6. The travel time from each cell center to each existing and potential station site was calculated by dividing the travel distance by the assumed speed of 25 m.p.h.

5.2 Maranzana

The Maranzana method consists of the following procedure:

1. Initialize

   Make an arbitrary selection from the possible station locations (in Alexandria, the current configuration).

2. District

   Assign each zone to the nearest fire station. A district is the collection of zones served from a single location. If any zone is equidistant from two or more stations, it is arbitrarily assigned to one of them.

3. Move

   For each district, determine if the current fire station location minimizes the objective function. If not, determine the location within that district which does so. This becomes the new fire station site for that district.

4. Terminate

   If the objective function in any district has been reduced, return to step 2. Otherwise terminate.

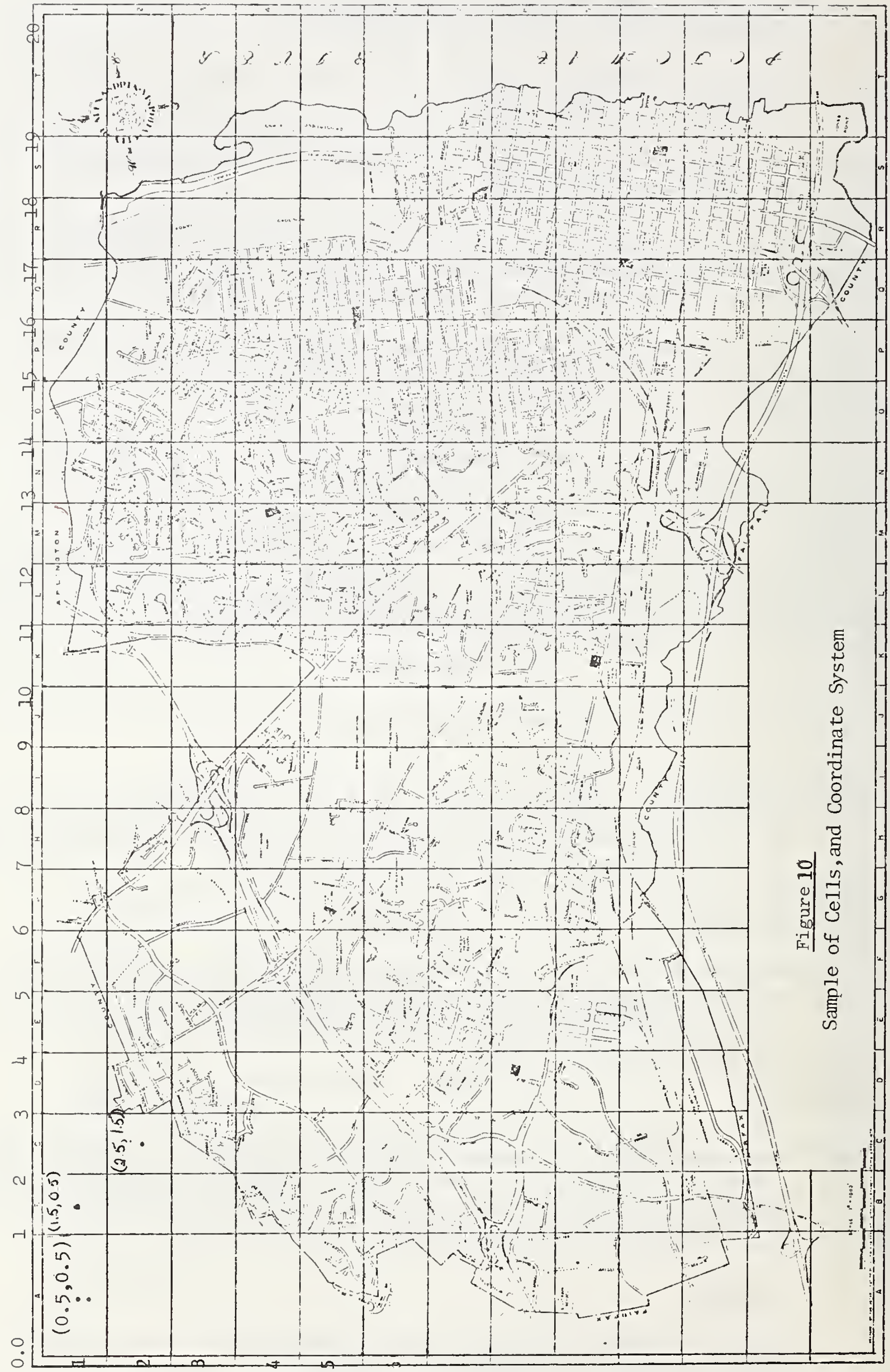


Figure 10
Sample of Cells, and Coordinate System

The locations selected in Alexandria by the Maranzana solution method are depicted in Figure 11.

The following equation:

$$\sum_i W_i t_i = W_1 t_1 + W_2 t_2 + \ldots + W_n t_n$$

where W_i is the number of calls from the i-th cell and t_i is the travel time to the i-th cell from the closest fire station, is used by the Maranzana method as the objective function to be minimized.

This application used 46K of computer core and needed five passages through Steps 2-4 to terminate. Each such iteration took 40 seconds of computer time on a UNIVAC 1108 with Exec 2 system. Total running time was 3 minutes and 26 seconds.

5.3 REDIST

REDIST uses almost the same objective function. In this case, the squares of the response times are used in order to make the districting more compact. However, the model also attempts to balance the work load (number of calls handled) among the various fire stations. Therefore, there is a major procedural change.

Steps one and two are the same as in the Maranzana approach. However, step three is modified to include:

Balance

Redistribute zones to be served from each fire station to equalize the number of calls handled by each station as much as possible.

The model then continues with step four of Maranzana. The locations and districts selected by the REDIST solution method in Alexandria are shown in Figure 12 (7).

REDIST ran with 17K of computer core and needed five iterations at 41 seconds per iteration. Total running time was 3 minutes and 35 seconds.

The application of these two methods of locating fire stations yielded two distinct locational patterns. These patterns are very much a function of the specific objective function used, the limitations imposed, and the assumptions made.

It is impractical to experiment by physically relocating fire stations and observing the results. Therefore, the analytic methods of Location theory are a valuable managerial tool for discovering reasonable alternatives to be tested through simulation. The two alternative locational patterns and the present configuration were compared and evaluated using the simulation model discussed in the next chapter.

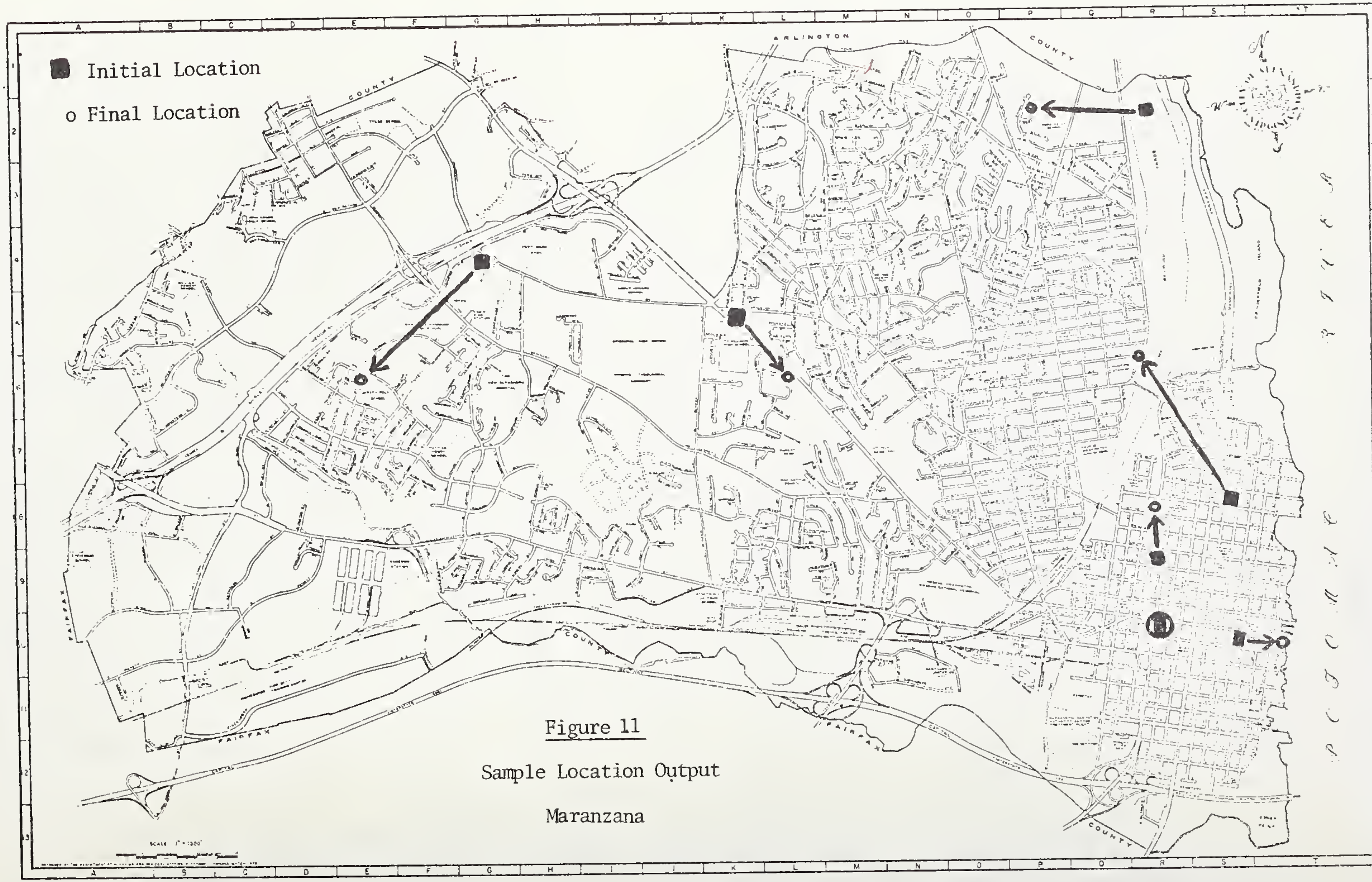


Figure 11

Sample Location Output

Maranzana

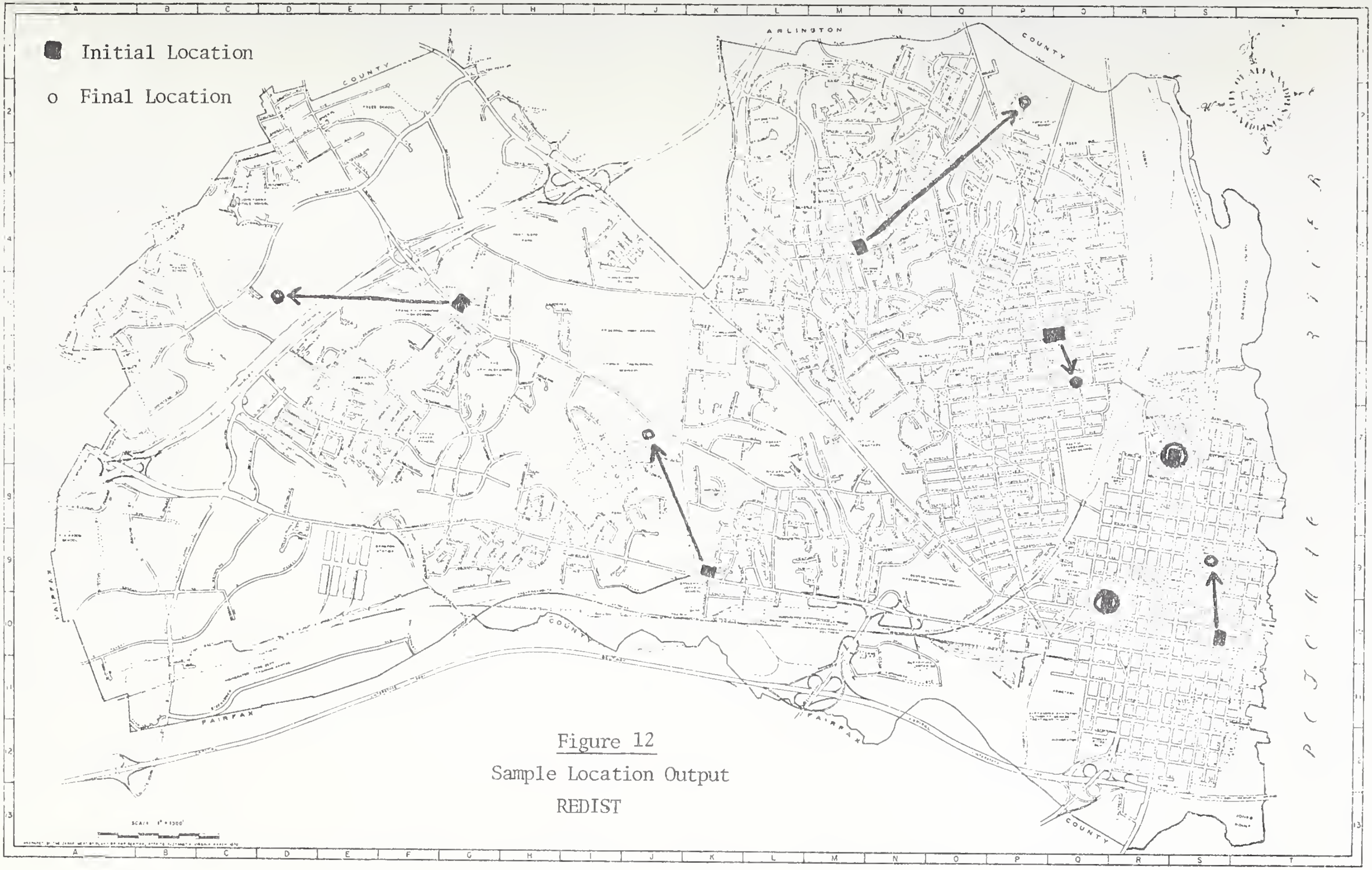


Figure 12
Sample Location Output
REDIST

6.0 SIMULATION

Simulation is a very useful tool for analytical management alternatives and deriving statistics which may be highly relevant to a decision-maker. This technique makes it possible to study the interactions of parts of a given system which may be too complex or too costly to observe in the real world or to treat by the use of analytical models. Detailed analysis of output from the simulation model may lead to a better understanding of the system and to suggestions for improving it.

Since analysts are forced to seek an appreciation and understanding of many facets of a system in order to properly develop the model and write the computer programs, their conclusions are less apt to be biased by particular inclinations and more apt to be workable within the system framework. It is also possible to introduce certain informational, organizational, and environmental changes into the model, and study their effects on the system operations.

In addition, a simulation model can provide a proving ground and a basis for comparison of results generated by analytical models. For example, the fire station locations specified by the two location models in Section 5.0 are evaluated in this section, and the Availability analysis statistics from Table 8 in Section 4.0 are compared with availability data generated by the simulation model.

6.1 Simulation Model

The simulation model SIM 2, which was applied to Alexandria, is relatively simple to describe [8]. A fire alarm will be referred to as a case. As simulated time progresses, cases enter the system; i.e., the fire department receives calls for service. The assignment portion of the model acts as the dispatcher by determining which particular resources will service a case. The selected resources then are represented as traveling to the case and remaining at the scene for a specified length of time. When the designated time elapses, the resources leave the scene and return to their stations. When the last resource leaves the scene of the case, that case is terminated.

6.2 Assumptions

The simulation model applied to Alexandria involved various assumptions:

1. Point to point travel times were represented by letting vehicles travel over a grid system, similar to the cell boundaries in Figure 10, formed by connecting the cell midpoints. All cases occurring within a cell were assumed to originate at the center of that cell. Travel speeds were assumed to be 22.5 m.p.h. when responding to emergency calls, and 15 m.p.h. at all other times. These speeds were viewed as reasonable by the Alexandria Fire Department for most of the area to be covered.

2. Travel distance from point to point was based on the "metropolitan metric," in which all movement occurs parallel to the grid-lines, the distance being from the (x,y) location of the fire station from which resources are dispatched to the grid coordinates of the center of the cell.

3. As vehicles traveled from point to point on the grid, it was assumed that they traveled the entire distance in the x direction before traveling in the y direction. A more refined analysis would use the actual transportation network in Alexandria, and the speeds possible over each road at the hour the call for service occurs. Travel times generated in this manner could be compared to actual runs.

   The simplified grid approach was used to permit a faster evaluation of the possible usefulness of the O.R. tools. The approximation is quite accurate for the densely populated eastern area of the city. In the western sector, the speeds are higher and the road network much sparser, resulting in longer distances but approximately the same travel times as the metropolitan metric would indicate. As a result, the simplified approach offers a first order approximation [9].

4. The time spent on the scene of the alarm was derived from the data as follows: For each responding company, a time of notification, t_1, and a time back "on the air" (in service), t_2, were available. The travel time was calculated as in steps 1-3. Using a start up time of .77 minutes [10], the on scene time derived was: $t_2 - t_1$ - total travel time - .77.

6.3 Simulation Model Input and Output

Required input for the model included, for each case:

1. The day and time the case occurred
2. An identification number for the case, such as its log number
3. The number of additional alarms for the case if more than the initial response was necessary
4. The location of the case, in (x,y) grid coordinates
5. A number indicating the type of case (public service, accidental alarm, fire, etc.)
6. The time of alarm, the on scene time, and the number of engine and truck resources utilized.

The output from SIM 2 consisted of two main parts. The first part provided a record of the inputs for each case and how the case was handled by the simulation model (e.g., companies dispatched and response times).

The second, major, part of the output consisted of summary data divided into six sections:

1. A summary of the simulation specifying:

   a. Total number of days simulated
   b. Total number of cases serviced
   c. Total number of resource hours spent servicing cases
   d. Mean average response time per case
   e. Number of cases of each type (public service, false alarms, etc.)
   f. Average response time of first arriving engine company
   g. Average duration of service time for cases of each type
   h. Average number of resource hours required for cases of each type

2. The work load and total time out of its home station for each individual resource

3. A breakdown of the utilization of the individual resources measured in resource hours by the day of the week

4. The distribution of responses for the last arriving pumper for cases where 1, 2, ..., 5 pumpers were dispatched

5. The availability of resources, indicated by the number of engines idle at any particular time.

The simulation model also printed out the numbers of those cases for which unusually long response times occurred. These case numbers may be used to return to the source data to reconstruct the specific situations involved. This information may suggest ways to modify dispatch or repositioning policies, or may motivate mutual aid agreements with neighboring counties in order to reduce the possibility of such extra-long response times.

The simulation used actual arrival times of alarms, and derived on-scene times. The availability of engine companies was generated by checking the number of idle companies every simulated hour throughout the simulated 123 day period. This availability data was used to generate availability distributions for each of the three time periods.

The data on engine company availability in period III derived from the simulation (using the present station locations) is compared with that from the queueing models in Table 9. There is a close agreement.

Table 9

Availability Distribution Using
Chaiken and Simulation Models

Number of Companies (N)	Probability of (N) Companies Busy	
	Simulation Model	Chaiken (Availability) Model
0	.827	.809
1	.099	.107
2	.025	.031
3	.040	.043
4	.007	.006
5	.001	.002
6	.001	.001
7	<0.001	.0002
8	<0.001	.0001

6.4 Evaluation of Location Alternatives

The simulation model was used to evaluate several alternative fire station location patterns, some of which were derived from the models in Section 5.0 and some of which were suggested by Alexandria officials. This was accomplished by comparing the operating statistics given by specific alternatives with those from the actual current configuration of stations.

These alternatives were:

1. Optimal location of fire stations as given by the Maranzana location method
2. Fire station locations as given by the REDIST method
3. Add an eighth station in the western part of Alexandria
4. Move the engine company in Station 1 into Station 3
5. Add Station 8; move the engine company currently in Station 1 to Station 3
6. Move the engine company in Station 1 to the new Station 8 location.

For each alternative, statistical distributions were collected separately for cases where one, two, and three engine companies responded, as shown in Table 10.

It is desirable to lower both the mean response times and the standard deviation (which measures the variability of the responses), by reducing the number of long response times. The differences in Table 10 are not sufficiently large to warrant conclusions without statistical analysis. Since the Alexandria Fire Department was actually planning to add an eighth station, further analysis was done on this alternative. Specifically, the response time statistics from the simulation model for this case were compared with those for the present station locations.

The distribution of response times for the last arriving engine produced varying results depending on whether 1, 2, or 3 engines were used for service.

Figures 14, 15, and 16 graphically show the frequency of different response times. The two lines are coded with symbols to indicate the alternative each represents. The two histograms in Figure 14 are close together over the whole response time range, and no appreciable difference is observed. However, Figures 15 and 16 show that there were a number of cases in which the second or third engine company dispatched would arrive sooner if Station 8 were added.

A standard statistical test (Kolmogorov-Smirnov) was used to determine if the two alternatives differed significantly. For one and two engine cases, no significant difference was found. However, three engine cases showed a significant difference at the 1% level of significance. Consequently, it may be concluded that the addition of Station 8 would significantly reduce last-engine response time for cases requiring three engine companies.

Table 10

Statistics for Different Alternatives

Present Locations	Mean Average Response Time (in minutes)	Standard Deviation	Median
First Engine	2.803	1.600	2.25
Second Engine	4.807	2.901	3.75
Third Engine	5.862	3.583	5.25
Maranzana			
First Engine	2.757	2.564	
Second Engine	4.936	2.881	
Third Engine	6.214	3.771	
Redist Locations			
First Engine	2.728	1.487	2.25
Second Engine	4.800	2.879	4.75
Third Engine	5.928	3.839	3.75
Add Station 8			
First Engine	2.633	1.383	2.25
Second Engine	4.447	2.875	3.75
Third Engine	5.07	2.881	4.25
Move Station 1 to 3			
First Engine	2.916	1.572	2.25
Second Engine	4.736	2.924	3.75
Third Engine	5.802	3.625	4.25
Add Station 8, Move 1 to 3			
First Engine	2.749	1.362	2.25
Second Engine	4.369	2.894	3.75
Third Engine	5.011	2.914	4.25
Move Station 1 to Station 8			
First Engine	2.886	1.622	2.25
Second Engine	4.707	2.871	3.75
Third Engine	6.002	2.602	5.25

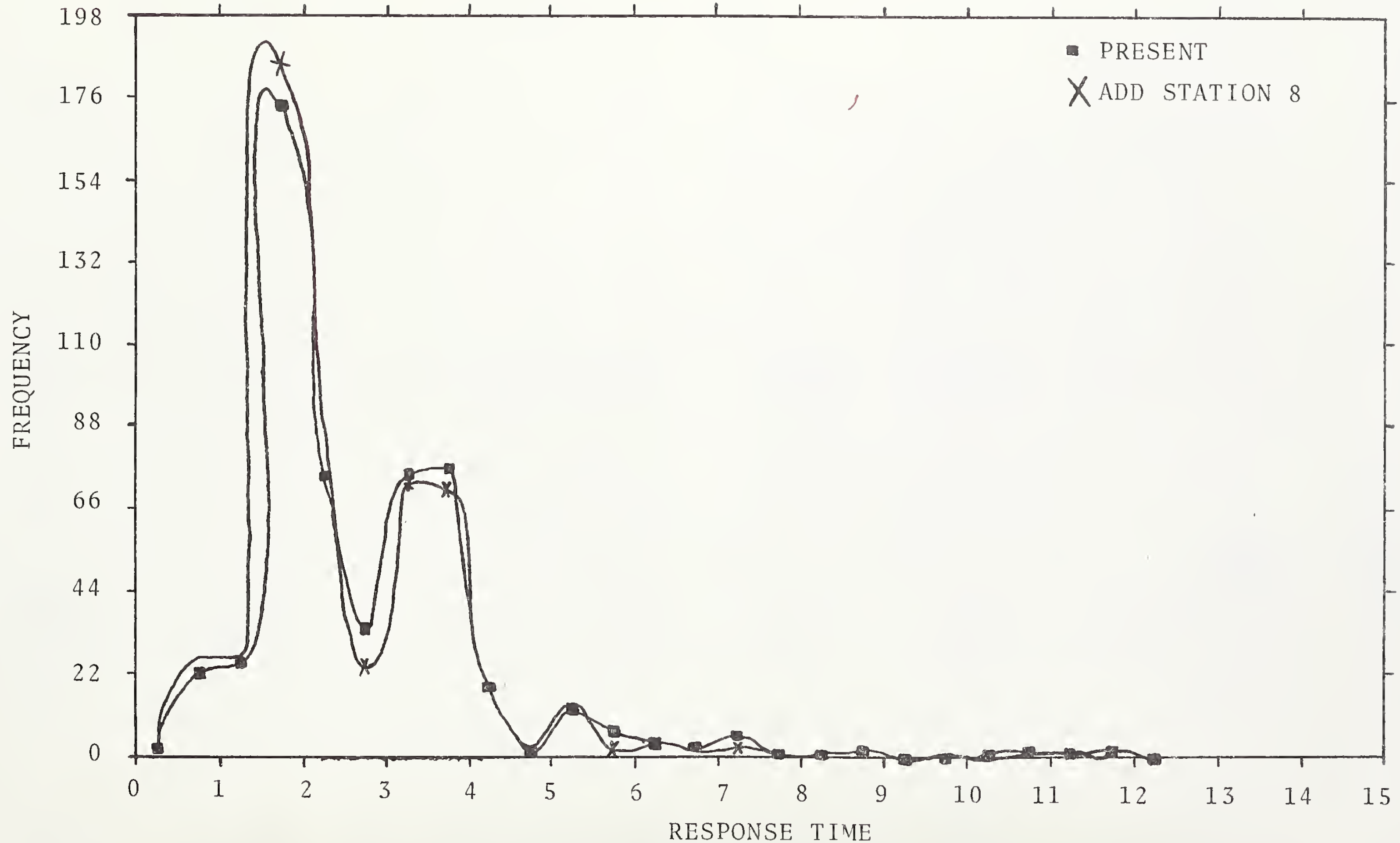


Figure 13

Distribution of Response Times for Last Arriving Engine When One Engine Company is Dispatched

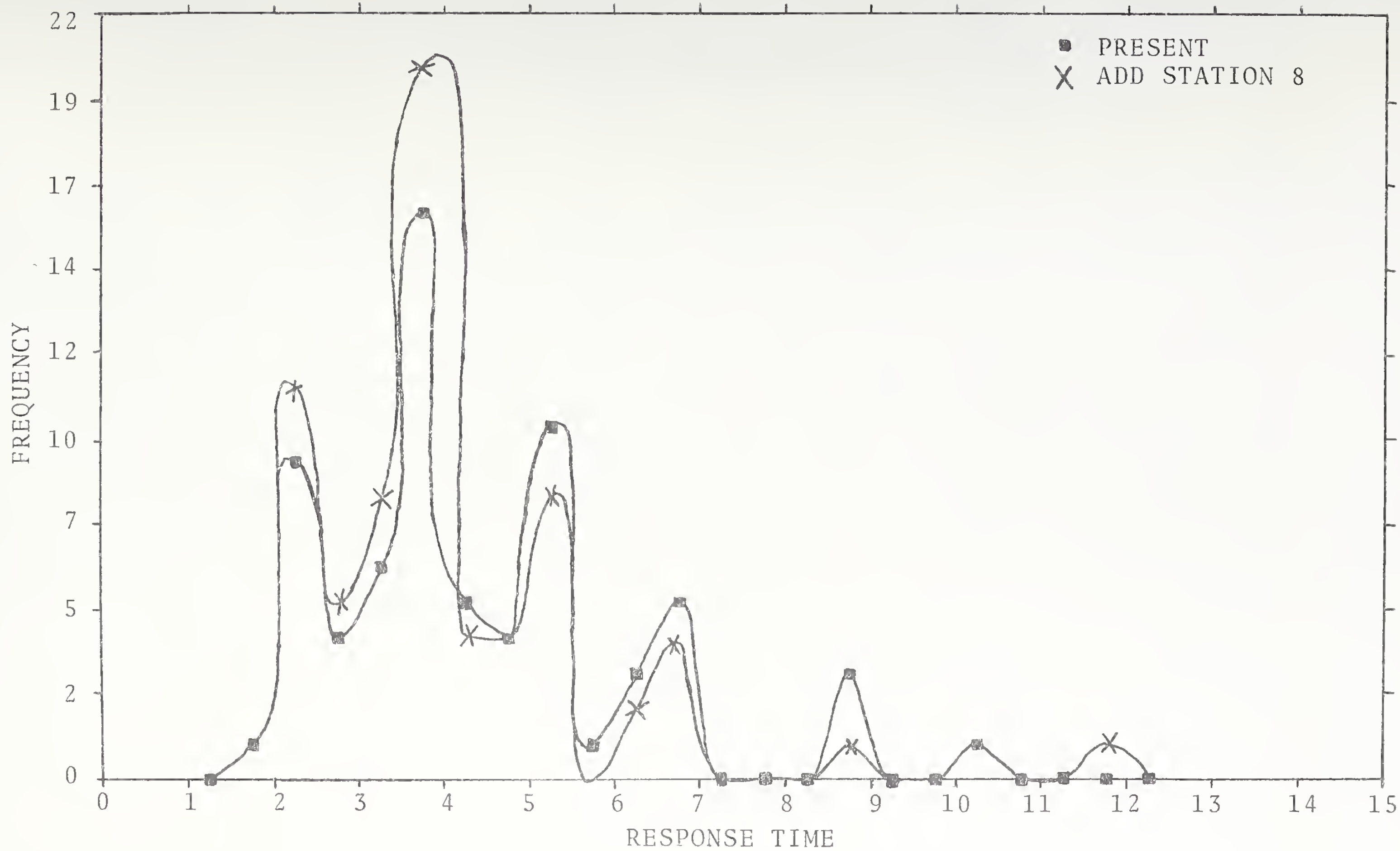


Figure 14

Distribution of Response Times for Last Arriving Engine
When Two Engine Companies are Dispatched

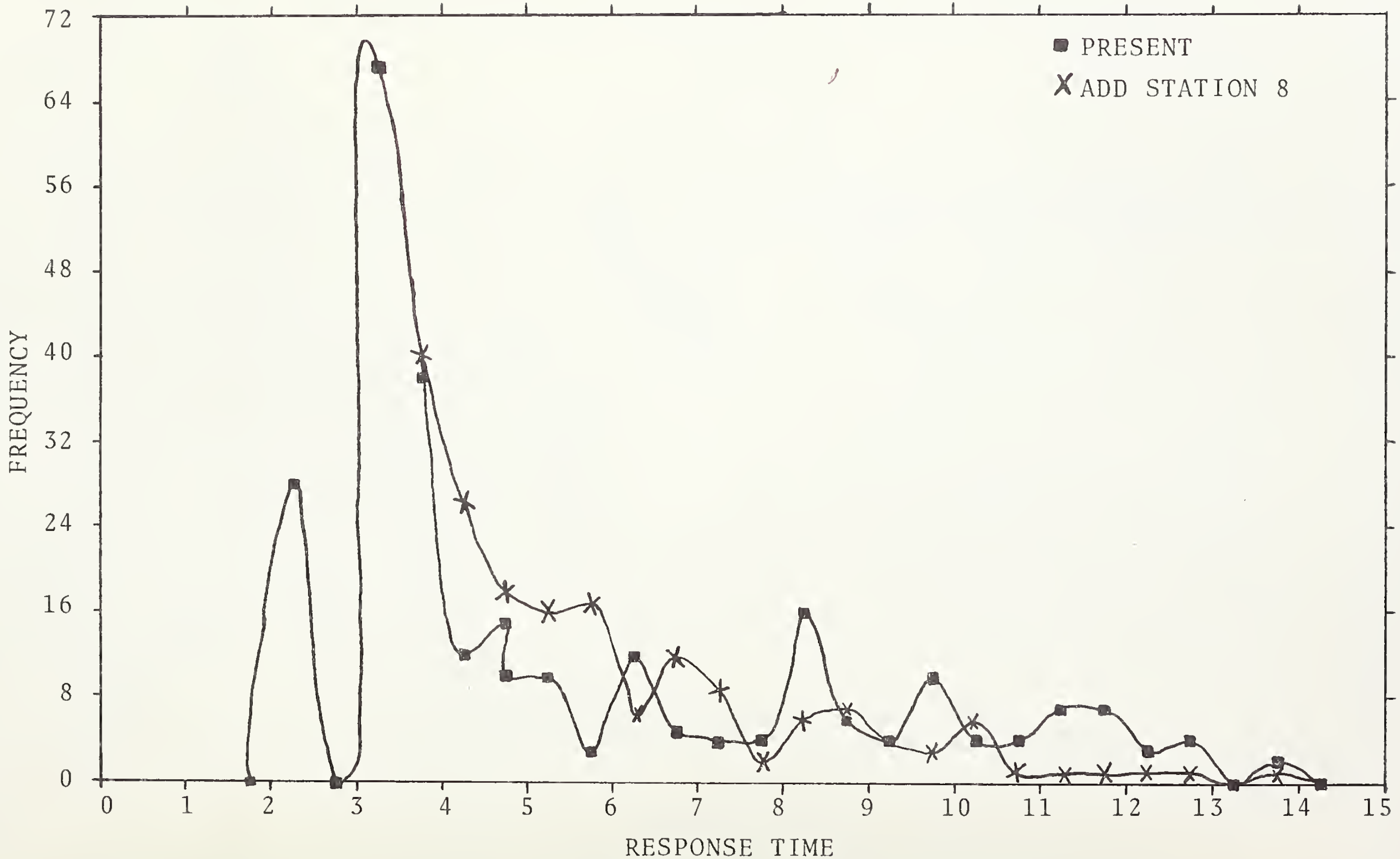


Figure 15

Distribution of Response Times for Last Arriving Engine
When Three Engine Companies are Dispatched

7.0 CONCLUSION

A pilot program was conducted with the cooperation of the Alexandria, Virginia Fire Department to evaluate the applicability and usefulness of selected Operations Research methods. These methods, in the form of computer programs, were modified and adapted to assure that they could be implemented to provide information which would facilitate fire department management. In this effort Queueing, Fire Station Location, and Simulation models were applied to data extracted from the historical records of the Alexandria Fire Department.

An important aspect of this study is the development of a preliminary methodology for analyzing certain features of fire service operations. This process consists of the following four steps:

(1) Data Analysis - collection and evaluation of historical data
(2) Availability Analysis - use of Queueing theory to determine probable demands for service
(3) Location Models - use of response times over a street network and fire service demand factors in an objective function to determine alternative fire station location configurations
(4) Simulation Model - use of a computer based model to compare various alternatives and to test results of the Availability Analysis and Location Models.

It is hoped that the information provided by this methodology may facilitate better management decisions based on a more complete understanding of the mechanisms involved in furnishing fire service for an area.

The simulation model used in Alexandria does not currently include provisions for such factors as:

1. Queueing of cases by the dispatcher
2. Delayed response time when resources are occupied
3. Interruption of "low priority" service when an urgent case occurs
4. Temporarily transferring resources into other depleted stations when necessary.

These provisions, although obviously important in modeling some fire departments, were not necessary in Alexandria because of the high degree of availability. However, the simulation model was purposely developed with a modular structure to facilitate adding such provisions as needed to adapt the model to apply to other fire departments.

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

Rising labor costs and increasing competition for tax dollars to provide urban services demand that a more precise methodology be used in the management of fire departments. A pilot program was conducted with the cooperation of the Alexandria, Virginia Fire Department to evaluate the applicability and usefulness of selected Operations Research tools. These tools, in the form of computer models, were modified and adapted to assure that they could be implemented to provide information which would facilitate fire department management. In this effort queueing, facility location, and simulation models were applied to sample data extracted from the historical records of the Alexandria Fire Department. It was established that such models do provide valuable information which may assist managerial decisions. This paper describes the city of Alexandria and its fire department, the O.R. models, output from their application, and evaluations of the output.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Alexandria; fire department; location; operations research; resource allocation; simulation; systems analysis.

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