Modeling of Firefighting Operations through Discrete Event Simulation

Esra Aleisa and Mehmet Savsar

Abstract—**This paper reports the results of applying discrete event simulation on firefighting operations in the State of Kuwait. The objective was reduce response times to reach fires in all districts to below five minutes. The Simulation of output runs were analyzed using ANOVA. The results were validated at 95% confidence level. Simulation turned to be an excellent tool for testing a major change without disturbing firefighting operations.**

Index Terms—**Firefighting, response time, simulation ANOVA.**

I. Introduction

In the United States of 2006, one person died in a fire accident approximately every 162 minutes and one person was injured every thirty two minutes [1]. Urban fire causes significant threat to the loss of lives and property. In the United States, building fires were responsible for over 3,000 deaths, 15,000 injuries and $9.2 billion in fire-related property damage in 2005 [2]. A common performance measure is the response time. It is a critical factor in the effectiveness of the firefighting services since well-set response time standards can minimize the risk to people and property loss. Response time is defined as the time from the receipt of a call of a fire incident to the arrival of the firefighting service to the incident site. Many Research efforts as in Huang et al. [3], Indriasari et al. [4], Erden and Coskun [5], and Wei and Juncheng [6], who conducted studies on optimal siting of Fire Stations in Singapore, South Jakarta, Istanbul and China, respectively, agreed on a response time of five minutes or less for firefighting services. Tzeng and Chen [7], on the other hand, who conducted their study in Taipei's international airport in Taiwan, aimed for a response time of no longer than three minutes for aircraft fire accidents. While Yang et al. [8] established response time ranges based on the fire risk category, ranging from four to five minutes for high risk fires to ten to twenty minutes for low risk ones, in the Derbyshire region, UK.

Murray and Tong [9] conducted their study in North Boston, USA, aimed for a response time of six minutes, broken down as follows: one minutes for the dispatcher to handle the call of service, one minutes for a fire company to get into their gear and depart, and four minutes of travel time. Determining the proper response time is critical in order to beat flashovers. Flashovers is defined as the point in time at which a structure fire is fully developed, so people are not likely to survive and property is unsalvageable [9].

A simulation model is developed to study the firefighting system in detail and to determine the effects of implementing different changes on response time. Discrete event simulation was used due to its ability to incorporate many of the constraints commonly found in large-scale systems [10]-[12]. The simulation model was constructed using Arena software. The results of the system were validated at a 95% confidence level. This means that the simulation model is valid representation of reality, which qualifies it to be used as medium for diagnostics and improvements.

II. Literature Review

Most work on improving fire stations operations aim to reduce response time. One of the earliest work in this area was conducted on fire station location involved simulation [13]. In his research Hogg [13] discussed some methods of optimal siting of fire stations were he aimed to minimize the sum of the financial loss from fire and the cost of providing the fire brigade. Another early research conducted by Monarchi et al. [14] have also used simulation to analyze alternative deployment strategies for urban fire suppression systems. Fitzsimmons [15] have used computer models for disseminating emergency ambulances to fire stations in an attempt to reduce response time. His research was the first to consider the urgency of response time reduction. Hendrick and Plane [16] have analyzed the deployment strategies for Denver's fire department. They used a simulation model to evaluate different fire companies' configurations. An extension to the aforementioned research was presented by Plane and Hendrick [17]. Halpern *et al.*[18] analyzed the effect of manning level in one and two-family residential fires in the city of Calgary, Canada. They established a relationship between manning levels and time needed to extinguish the fire by using an activity network approach.Badri et al. [19] have considered multiple objectives that incorporate both travel times and travel distances from stations to demand sites. They also considered political criteria in their model and used a programming modeling technique to solve the problem. Tzeng and Chen [20] developed a location model based on a fuzzy multi-objective approach to help in determining the optimal number and sites of fire stations at an international airport. Due to the combinatorial complexity of their formulation they employed a genetic algorithm (GA) to determine the optimal number and sites of fire stations in Taipei's international airport. Later, Patricio Pedernera et al. [21] developed a dynamic programming model which

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evaluates the different possible combinations of fire stations' locations on the basis of the coverage which each location provides to the system, maximizing the surface area under coverage. Their model was applied to the Forest Fire Protection Program system in Chile. Huang et al. [3] used the Ant Algorithm to solve a fuzzy model characterized by a large scale Linear Feature Covering Problem (LFCP), by first transforming the continuous problem into a discrete one using the Geographic Information System (GIS). They applied the ant algorithm due to its ability to solve novel Multi-Objective problems for solving large scale location problems due to its new local search measure [3, 22]. Yanga et al.[23] have also developed a fuzzy multi-objective programming model for the optimization of fire station locations but through genetic algorithms.

III. Fire Operations in Kuwait

There are twenty stations that belong to the firefighting sector. Each station has a specific coverage area. However, if a station is busy with an incident and another incident occurs at the same time in its coverage area, then the nearest station is assigned to cover. Our field study shows that the firefighting sector has attended 14,714 incidents last year. 30.4% of these incidents were actual fires. Fire incidents are classified as: residential areas, commercial areas, other areas, aviation transportation, marine transportation, and land transportation. Percentages of these incidents are shown in Table I. The remaining 69.6% are non-fire incidents; these are classified as rescue, good intent calls, service calls, occasion safety, false calls, and others with related percentages shown in Table II. Good intent calls had the highest percentage compared to the other types of calls.

TABLE I: Classification of Fire Incidents Attended by the Firefighting Sector

Fire Incidents	*Number of Occurrence*	*Percentage*
Residential Areas	855	19.13
Commercial Areas	476	10.65
Other Areas	2,256	50.47
Aviation Transportation	1	0.02
Marine Transportation	11	0.24
Land Transportation	871	19.49
Total	*4,470*	*100*

TABLE II: Classification of Fire Calls Received by Firefighting Sector

Non-fire incidents	*Number of Occurrence*	*Percentage*
Rescue	2,010	19.62
Good Intent Calls	5,406	52.75
Service Calls	1,964	19.16
Occasion Safety	524	5.11
False Calls	280	2.73
Others	64	0.63
Total	*10,248*	*100*

IV. Simulation System Parameters

The entities consists of calls that arrive to the emergency service center and delivered to the fire stations. These are transformed into information that is delivered to the fire station. Then, eventually to firefightersmovement to the place of the incident.

The operating policy in the general simulation network model is that each station is able to receive one incident only; otherwise incidents are delivered to the next nearest available station. The system simulation model length is designed to cover 365 day, 24 hours/day. The simulation consisted of thirty replications.

A. Statistical Data Fitting

We define denote the firefighting time intervals as:

1) T_i = Time duration to move to the incident place.
2) *Tf= Time duration for firefighting.*
3) *Ts = Time* duration *to return back to t*he station.

The fitting to statistical data distributions for the above intervals are shown in Table III.

TABLE III: Statistical Data Fitting for Arrival of Fire Related Incidents for Some Fire Stations

Stations	*Ti (min)*	*Tf (min)*	*Ts (min)*
Madina	0.5+LOGN (8.65,9.23)	0.5+GAMM (9.05, 1.09)	4+WEIB(23.3, 0.909)
Shuwaikh Industrial	1.5+GAMM (2.37,3.29)	0.5+LOGN (9.52, 21.6)	4+WEIB(14.1, 0.722)
Hilaly	0.5+WEIB (8.51, 1.53)	0.999+WEIB (14.2, 0.505)	2+EXPO(20.9)
Doha	6	10	24
Shohada	0.5+GAMM (5.5, 1.1)	0.5+WEIB (8.42, 1.32)	2.5+WEIB (22.9, 1.15)
Sulaibikat	1.5 +WEIB (6.56, 1.73)	0.5+LOGN (9.32, 13)	0.5+ERLA (8.82, 2)

TABLE IV: Number of Accidents from the Actual and Simulation Model

Month	*Simulation Model Output*	*Actual Incidents*
January	1113.87	1208
February	1034.80	1051
March	977.03	1236
April	1077.43	1277
May	1540.87	1332
June	1260.77	1297
July	1422.90	1300
August	1669.53	1319
September	1375.20	1207
October	1757.30	1208
November	1685.27	1081
December	1155.80	1198
Total incident	16070.77	14714
Mean	1226.17	1339.23
St-dev	7867.79	75961.2

V. Model Validation

Model validation indicates if the system is a valid representation of reality. Table IV summarizes the total number of incidents per month for the real as-is system and for the simulation model. In order to test the hypothesis on equality of the means, first we perform the test on equality of variances as by having the null hypothesis as $H_0 : \sigma_1^2 = \sigma_2^2$ and the alternative hypothesis *as* $H_1 : \sigma_1^2 \neq \sigma_2^2$ the resultant *P-value* = .001. The decision rule is to reject H_0 if the P-value is less than the significance level ofα= 0.05. Hence, we rejected H_0 and concluded that the two population variances are not equal. Next, we need to test the equality of two means. The null hypothesis here is $H_0 : \mu_1 = \mu_2$ while the alternative one $H_1 : \mu_1 \neq \mu_2$. The resultant P-value = 0.2.

TABLE V: OUTPUT OF SIMULATION MODEL

Fire Station	*I. Avg. Utilization (%)*	*II. Avg. Response Time (Min)*	*III. Avg. Number of Incidents >10 Min*	*IV. Response Time/Utilization*	*V. Incidents >10 Min/Utilization*
Jaleeb	15.89	11.85	643.07	0.746	40.470
Alqurain	11.47	11.52	556.9	1.004	48.553
Salmiya (south)	8.25	8.556	328.3	1.037	39.794
Farwaniya	7.0675	7.182	176.83	1.016	25.020
Mangaf	6.6316	8.928	356.63	1.346	53.777
Hawalli	6.4816	114.952	577.83	17.735	89.149
Mushrif	6.3942	13.206	353.87	2.065	55.342
Jahra	6.3284	9.96	272.4	1.574	43.044
Jahra Crafts	6.3246	13.89	414.57	2.196	65.549
Salmiya	5.9923	7.404	86.5333	1.236	14.441
Shohada	5.2795	8.028	207.3	1.521	39.265
Sulaibikat	5.0643	8.856	280.83	1.749	55.453
Mina Abdulla	4.676	18.264	171.17	3.906	36.606
Hilaly	4.1738	9.666	180.8	2.316	43.318
Mubarak Alkabeer	4.1552	18.438	179.63	4.437	43.230
Ardiya	4.0306	10.698	159.5	2.654	39.572
Shuwaikh Industrial	3.6691	10.758	263.83	2.932	71.906
Airport	3.101	5.448	18.533	1.757	5.976
Madina	2.8313	10.698	123.9	3.778	43.761
Fahaheel	2.6462	7.02	61.9	2.653	23.392
Military Airport	2.4868	15.63	69.7333	6.285	28.041
Ahmadee	1.6888	8.826	61.4	5.226	36.357
Nuwaiseeb	1.2514	15.198	88.4667	12.145	70.694
Ras Alsalmiya	1.1238	26.7	15.6997	23.759	13.970
Shoaiba Industrial	0.941	16.296	39.4667	17.318	41.941
Wafra	0.7281	16.482	56.2	22.637	77.187
Shoaiba Marine	0.7062	42.198	7.5	59.754	10.620
Zoor	0.6918	21.606	20	31.232	28.910
Doha (Technical rescue)	0.597	7.506	0	12.573	0.000
Sabhan	0.4661	20.196	23.6333	43.330	50.704
Salmi	0.4257	17.466	23.8333	41.029	55.986
Khour al-Subiya	0.3838	29.514	21.1333	76.899	55.063
Shuwaikh Marine	0.3759	10.692	33	28.444	87.789
Subiya	0.3354	16.434	27.6	48.998	82.290
Failaka Maeine	0.3107	8.526	13.9333	27.441	44.845
Abdili	15.89	16.464	13.6	1.036	0.856

Using the same decision rule, since test statistic of 0.2 was larger than significance level of *0.05,* we failed to reject H_0 and conclude that both population means are equal at a 95% confidence level. Finally, we constructed a confidence interval on the difference between the two population means. We are 95% confident that the difference between the two means is between [-68, 294]. Since zero is within this interval, we can conclude that both population means are equal at a 95% confidence level. Our model is a valid representation of reality. Other variables were also tested to ensure system validation.

VI. ANALYSIS OF SIMULATION OUTPUT

Table V shows the outputs from the simulation model. As it is seen in the table, Jileeb Shyookh area had the highest station in utilization and Shoaiba Marine had the highest response time. While response time is an important measure, the number of incidents for which delay time exceeds ten minutes is a main concern that has to be addressed in improving the fire station operations. Utilization of a station only tells us whether or not the station is over-loaded. An important measure that could be developed is the combination of these measures. We have calculated a measure based on *response time/utilization*, for which smaller value indicates better performance. We have also devised another measure based on *number of incidents exceeding 10 minutes/utilization*, which is also required to be low. As it can be seen from the Table VI, with respect to response time/utilization, Jaleeb station performed the best with a minimum value of 0.746 and Khour Al-Subiya performed worst with a maximum value of 76.899. With respect to number of incidents exceeding 10 minutes/utilization, as shown in column V of Table VI, Doha (Technical Rescue) station performed best with a value of 0, while Hawalli performed worst with a value of 89.149.

VII. Analysis of Variance

In this section, we use the analysis of variance (ANOVA) to identify the factors of legitimate effect on response time reduction. We conducted the experiments using 2^3 factorial designs on our validated simulation models. The three factors consist of:

1) Using navigation device in the vehicle.
2) Using a centralized network that links the emergency service centers and fire stations
3) Using the phone number to locate incidence position (when land lines are used)

Each factor is assigned two levels as follows:

1) Using the current procedure
2) Using the suggested option

TABLE VI: Anova Model

No	Label	(A)	(B)	AB	(C)	AC	BC	ABC	Replication 1		Replication 2	
									Response time	*No. of delayed incident*	*Response time*	*No. of delayed incident*
1	(1)	-1	-1	1	-1	1	1	-1	7.49	70	7.72	85
2	a	1	-1	-1	-1	-1	1	1	4.56	0	4.59	0
3	b	-1	1	-1	-1	1	-1	1	4.08	0	4.07	0
4	Ab	1	1	1	-1	-1	-1	-1	3.57	0	3.58	0
5	C	-1	-1	1	1	-1	-1	1	3.97	0	3.98	0
6	Ac	1	-1	-1	1	1	-1	-1	3.33	0	3.32	0
7	Bc	-1	1	-1	1	-1	1	-1	3.07	0	3.08	0
8	Abc	1	1	1	1	1	1	1	2.48	0	2.83	0

For analysis of suggested improvements, we conducted full factorial design of the experiments with 2^3 design formed by treatment combinations. Minitab software was used to analyze the results. Table VI shows the algebraic signs for the factors and levels assigned.

Factor C has the highest effect, followed by B, and then by A. The F-values of the main effects, the 2-Way interaction, and the 3-Way interaction are high. We conclude that the main effects of the factors and their interactions are all significant.

VIII. Results of the Improved Model

After determining significant factors affecting the response time, we re-run the simulation code while using the ANOVA results. On average, the simulation model suggests the average response time will reduce rom 7.3 minutes to around 3.0 minutes. The following tests are performed in order to statistically compare the current system with the improved system. First we test the equality of two population variances: using H_0: $\sigma_1^2 = \sigma_2^2$ and H_1: $\sigma_1^2 \neq \sigma_2^2$. The corresponding P-value = 0.00. Indicating by that that the two population variances are not equal. Testing the equality of two population means for the current and improved system: with H_0: $\mu_1 = \mu_2$ and H_1: $\mu_1 \neq \mu_2$ results in a P-value = 0.00 which supports the hypothesis that the current and improved response times to statistical differ.

IX. Conclusion

In this study, we have applied discrete event simulation to model firefighting services of the state of Kuwait. All fire stations in all governorates were analyzed in an attempt to reduce response times to incidence place. Thus, saving more human life and to minimizing damage to property. The data was collected over a five years period and a simulation code was generated for all existing fire stations and associated emergency service rooms. The simulation model of the current simulation was validated at a 95% confidence level. Therefore, it was qualified to be used as an experimentation medium to test different scenarios and technologies that aim to reduce response time. Experiments were carried out using 2^3 factorial designs and analyzed to indicate those factors that will contribute most to response time reduction. Analysis of the production showed, that the best scenario involved the introduction of centralized systems and navigation technology. The simulation with the technology introduced has succeeded in reducing the response time by 32%. Simulation turned out to provide valuable information and insight of problems in the current systems. Also, it enabled testing proposed solutions without disturbing the current system or jeopardising lives and properties.

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