Optimizing Ladder Truck and Car Lift Occupancy in Fire and Rescue Departments Using Queuing Theory

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Abstract: The article presents the results of research conducted using the theory of queuing in order to optimize the number of special equipment in the fire and rescue units of the Ministry of Emergency Situations and to improve the overall efficiency of its utilization. The study emphasizes that the presence of hazards, the number of which has been constantly increasing in recent years, has inevitably led to a rise in accidents, explosions, fires, catastrophes, and other emergencies of natural, man-made, and environmental origin. This trend has placed growing demands on fire and rescue units, highlighting the need for scientifically based methods of resource planning and optimization. Within the framework of the research, the mathematical apparatus of queuing theory was applied to evaluate the workload of fire and rescue units, to identify patterns in emergency call arrivals, and to determine the optimal number of special equipment units required under varying conditions. Statistical analysis confirmed that the flow of emergency calls can be described by a Poisson distribution, while service times and fire extinguishing durations follow exponential distributions. These probabilistic models provided the necessary foundation for optimization, ensuring rational allocation of equipment and minimizing delays in response. Particular attention was paid to the challenges posed by rapid urban development. Large industrial facilities, critical infrastructure, and especially the sharp increase in the number of high-rise buildings create new fire safety risks. Ensuring effective fire protection in such environments is a pressing issue today. The results of the study contribute to the development of scientifically grounded strategies for resource optimization, offering practical recommendations for improving the reliability and efficiency of fire and rescue operations in modern urban settings.

1 INTRODUCTION

Of the 193 high-rise buildings currently under construction in the republic, 141 are up to 50 meters high (up to 16 floors), 47 are 50–100 meters high (16–33 floors), and 5 exceed 100 meters (33–51 floors). Of these high-rise buildings, 163 are residential.

The largest number of high-rise buildings (61) is located in the city of Tashkent, including the 51-storey "Nest One" building under construction in the Tashkent City area and the 25-storey "Akay City" residential complex in the Mirzo-Ulugbek district. In addition, 40 residential complexes are being built in the Samarkand region, 25 in the Fergana region, and 19 in the Andijan region [1].

In this regard, in 2020, the Ministry of Emergency Situations developed requirements for the fire protection of high-rise buildings. As a result, ShNK of the Ministry of Construction 2.01.02-04 "Fire Safety of Buildings and Structures" was introduced as an annex to the urban planning norms and rules[1].

One of the main tasks of ensuring fire safety is the elimination of fires at the initial stage and the prevention of fire spread in high-rise buildings.

According to the current fire safety regulations for buildings and structures (GNK 2.01.02-04[1]), fire and rescue units should be located at a distance of 1–2 km from high-rise buildings. However, the large-scale construction currently underway has resulted in significant distances between fire and rescue stations and high-rise buildings. In particular, 94 high-rise buildings are located at a distance of 3 km, 61 at a

[1] https://www.scribd.com/document/878380851/
SHNK-2-01-02-04-En-Fire-Safety-of-Buildings-and-Facilities

distance of 3–5 km, 37 at a distance of 5–8 km, and one building at a distance of 8 km.

It should be noted that there are currently no specialized fire and rescue units dedicated to eliminating emergencies and fires in high-rise buildings. Moreover, high-rise buildings are insufficiently equipped with special ladders and aerial platforms for fire and rescue operations. According to regulatory requirements, 304 ladders and aerial platforms are required; however, only 65 units (21.4%) are currently available, resulting in a shortage of 239 units [1].

2 RESEARCH OBJECTIVES

This section outlines the main aims and research directions pursued in this study.

The objectives are formulated to ensure a systematic approach to optimizing the number and utilization of special equipment in fire and rescue units.

- to analyze the presence and growth of hazards that lead to an increasing number of accidents, explosions, fires, disasters, and other natural, man-made, and environmental emergencies;
- to justify the need for rational allocation and use of special equipment in fire and rescue units;
- to apply queuing theory methods to determine the optimal number of special equipment units;
- to address the issues of ensuring fire safety at large facilities and in high-rise buildings as a relevant and pressing research direction.

As a result of the above circumstances, the world began to design and create special systems designed, first of all, to ensure the safety of people in various situations that threaten life and health. The design and development of such systems required the creation and use of new scientific approaches, methods, and theories.

To solve such problems, reliability theory, queuing theory, game theory, new optimization methods such as linear, nonlinear, dynamic programming and others, united under the name “operations research,” arose. To prevent and eliminate the consequences of all types of emergency situations described above, special methods and methods have been developed.

According to the analysis of the research work carried out in this direction, in the conducted scientific research, sufficient research work has not been carried out to optimize the amount of special equipment in fire and rescue units and to improve the scope of application of this method, similar approaches were applied in [2]-[4].

The research was carried out using the queuing theory method to optimize the amount of special equipment in the fire and rescue units of the Ministry of Emergency Situations, and increase the efficiency of using fire and rescue special equipment [5].

The study adopted fire-rescue ladders and vehicle lifts directly used to extinguish fires and carry out rescue operations in high-rise buildings.

The statistics of fires in the city of Tashkent for 5 years was analyzed and the year with the largest number of fires among them was selected (see Table 1).

Table 1 presents the distribution of fire incidents in Tashkent over a five-year period. The parameter k represents the number of fires recorded in one day, while m_k indicates the number of days with the corresponding number of fires. For example, when k=0, m_k=1, meaning there was only one day without any fire. The most frequent case is k=5, observed on 63 days, which shows that five fire calls per day is the most typical occurrence. Extremely high values, such as 30 or 32 fires per day, are very rare and occurred only once. This distribution allows researchers to analyze the dynamics of fire incidents and apply queuing theory for optimizing fire-rescue resources.

Table 2 summarizes the annual statistics of daily fire calls in Tashkent within the range of 0–16 fires per day. Here, k denotes the number of fires per day, and m_k shows the number of days in which that value occurred. The data indicate that the most frequent number of daily fire calls is k=5 (m_k=65), followed by k=4 (m_k=44) and k=6 (m_k=43). The frequency of higher fire counts gradually decreases, and values above 10 fires per day are relatively rare. This distribution provides important information for determining the typical workload of fire-rescue units and planning the required number of vehicles, ladders, and other resources.

Table 1: Distribution of fire incidents in Tashkent over a five-year period.

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
m_k	1	9	26	37	63	51	43	27	22	21	15	13	11	6	5	1
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
6	1	1	2	1	1		1									1

Table 2: Annual statistics of daily fire calls in the range of 0–16 fires per day in Tashkent.

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
m_k	1	6	17	27	44	65	43	39	34	31	25	15	9	5	2	1	1

The theoretical probability that the number of calls [5], [6] per day is 0

$$P_0(\tau) = e^{-\lambda\tau} = e^{-6.42\cdot 1} = 0.00147.$$

The theoretical probability that the number of calls will be equal to 1 for an interval of length τ (within one day)

$$P_1(\tau) = \frac{\lambda\tau}{\kappa} P_{1-1}(\tau) = P_0(\tau)\cdot\lambda = 0.00147\cdot 6.42 = 0.00943.$$

The theoretical probability that the number of calls will be equal to 2 for an interval of length τ (within one day)

$$P_2(\tau) = \frac{\lambda\tau}{2} P_{2-1}(\tau) = P_1(\tau)\cdot\lambda/2 = 0.00946\cdot 6.42/2=0.030294.$$

The theoretical probability that the number of calls will be equal to 3 for an interval of length τ (within one day)

$$P_3(\tau) = \frac{\lambda\tau}{3} P_{3-1}(\tau) = P_2(\tau)\cdot\lambda/3 = 0.0303\cdot 6.42/3=0.0648.$$

The theoretical probability that the number of calls will be equal to 4 for an interval of length τ (within one day)

$$P_4(\tau) = \frac{\lambda\tau}{4} P_{4-1}(\tau) = P_3(\tau)\cdot\lambda/4 = 0.06499\cdot 6.42/4=0.1040.$$

The theoretical probability that the number of calls will be equal to 5 for an interval of length τ (within one day)

$$P_5(\tau) = \frac{\lambda\tau}{5} P_{5-1}(\tau) = P_4(\tau)\cdot\lambda/5 = 0.1043\cdot 6.42/5=0.1336.$$

The theoretical probability that the number of calls will be equal to 6 for an interval of length τ (within one day)

$$P_6(\tau) = \frac{\lambda\tau}{6} P_{6-1}(\tau) = P_5(\tau)\cdot\lambda/6 = 0.1339\cdot 6.42/6=0.1429.$$

The theoretical probability that the number of calls will be equal to 7 for an interval of length τ (within one day)

$$P_7(\tau) = \frac{\lambda\tau}{7} P_{7-1}(\tau) = P_6(\tau)\cdot\lambda/7 = 0.1433\cdot 6.42/7=0.1311.$$

The theoretical probability that the number of calls will be equal to 8 for an interval of length τ (within one day)

$$P_8(\tau) = \frac{\lambda\tau}{8} P_{8-1}(\tau) = P_7(\tau)\cdot\lambda/8 = 0.1314\cdot 6.42/8=0.1052.$$

The theoretical probability that the number of calls will be equal to 9 for an interval of length τ (within one day)

$$P_9(\tau) = \frac{\lambda\tau}{9} P_{9-1}(\tau) = P_8(\tau)\cdot\lambda/9 = 0.1054\cdot 6.42/9=0.07505.$$

The theoretical probability that the number of calls will be equal to 10 for an interval of length τ (within one day)

$$P_{10}(\tau) = \frac{\lambda\tau}{10} P_{10-1}(\tau) = P_9(\tau)\cdot\lambda/10 = 0.07524\cdot 6.42/10=0.0481.$$

The theoretical probability that the number of calls will be equal to 11 for an interval of length τ (within one day)

$$P_{11}(\tau) = \frac{\lambda\tau}{11} P_{11-1}(\tau) = P_{10}(\tau)\cdot\lambda/11 = 0.0483\cdot 6.42/11=0.02812.$$

The theoretical probability that the number of calls will be equal to 12 for an interval of length τ (within one day)

$$P_{12}(\tau) = \frac{\lambda\tau}{12} P_{12-1}(\tau) = P_{11}(\tau)\cdot\lambda/12 = 0.02819\cdot 6.42/12=0.015.$$

The theoretical probability that the number of calls will be equal to 13 for an interval of length τ (within one day)

$$P_{13}(\tau) = \frac{\lambda\tau}{13} P_{13-1}(\tau) = P_{12}(\tau)\cdot\lambda/13 = 0.0150\cdot 6.42/13=0.00743.$$

The theoretical probability that the number of calls will be equal to 14 for an interval of length τ (within one day)

$$P_{14}(\tau) = \frac{\lambda\tau}{14} P_{14-1}(\tau) = P_{13}(\tau)\cdot\lambda/14 = 0.00744\cdot 6.42/14=0.0034.$$

The theoretical probability that the number of calls will be equal to 15 for an interval of length τ (within one day)

$$P_{15}(\tau) = \frac{\lambda\tau}{15} P_{15-1}(\tau) = P_{14}(\tau)\cdot\lambda/15 = 0.00341\cdot 6.42/15=0.001458.$$

The theoretical probability that the number of calls will be equal to 16 for an interval of length τ (within one day)

$$P_{16}(\tau) = \frac{\lambda\tau}{16} P_{16-1}(\tau) = P_{15}(\tau)\cdot\lambda/16 = 0.001461\cdot 6.42/16=0.000585.$$

Table 3: Comparison of empirical and theoretical probabilities of fire occurrences and Pearson chi-squared test results.

K	m_k	W_k	P_k	W_k - P_k	$(W_k - P_k)^2/P_k$
0	1	0,002739726	0,00147	0,0012697	0,001096738
1	6	0,016438356	0,0094374	0,007001	0,005193527
2	17	0,046575342	0,0302941	0,0162813	0,008750244
3	27	0,073972603	0,0648293	0,0091433	0,001289548
4	44	0,120547945	0,104051	0,016497	0,002615541
5	65	0,178082192	0,1336015	0,0444807	0,01480923
6	43	0,117808219	0,1429536	-0,0251454	0,004423035
7	39	0,106849315	0,1311088	-0,0242595	0,004488826
8	34	0,093150685	0,1052148	-0,0120642	0,001383303
9	31	0,084931507	0,0750533	0,0098782	0,001300141
10	25	0,068493151	0,0481842	0,020309	0,00855994
11	15	0,04109589	0,028122	0,0129738	0,005985362
12	9	0,024657534	0,0150453	0,0096122	0,006141132
13	5	0,01369863	0,0074301	0,0062686	0,005288645
14	2	0,005479452	0,0034072	0,0020722	0,001260318
15	1	0,002739726	0,0014583	0,0012814	0,001126036
16	1	0,002739726	0,0005851	0,0021546	0,007933601
Total	365				0,081645166

Table 4: Critical values of the chi-squared (χ^2) distribution for different degrees of freedom and significance levels [7].

The number of free degrees k	α degree of significance					
	0.01	0.025	0.05	0.95	0.975	0.99
1	6.635	5.024	3.841	0.0039	0.001	0.0002
2	9.210	7.378	5.991	0.1026	0.0506	0.0201
3	11.345	9.348	7.815	0.3519	0.2158	0.1148
…	…	…	…	…	…	…
14	29.141	26.119	23.685	6.571	5.629	4.660
15	30.578	27.488	24.996	7.261	6.262	5.229
16	32.000	28.845	26.296	7.962	6.908	5.812

Using the above formulas m_k, $W_k(\tau)$, $P_k(\tau)m_k$,-the number of days of fire emergency exits k times during the year, $W_k(\tau)$–empirical probabilities that the number of calls in a time interval of length τ (1 day) is k, $P_k(\tau)$-Wk (1) in our example, where we consider the values of the theoretical probability that the number of calls will be k in the time interval τ (1 day), Table 5 shows the detailed statistical processing of annual fire call data in Tashkent, covering the distribution of daily fire frequencies. The column K represents the number of fires per day, while m_k denotes the number of days with the corresponding fire count, with a total of 365 days in the observation period. The relative frequencies W_k were obtained by dividing m_k by the total number of days, providing the empirical probabilities of fire occurrences. The column P_k contains the theoretical probabilities calculated based on the assumed distribution law (likely Poisson distribution). The difference W_k - P_k reflects deviations between experimental and theoretical probabilities, while the last column $(W_k - P_k)^2 / P_k$ presents the contribution of each category to the Pearson chi-squared test statistic. The total value χ^2 = 0.081645166 indicates a very close agreement between empirical data and the theoretical distribution, confirming the adequacy of the chosen probabilistic model for describing fire occurrences in Tashkent.

Table 4 presents the critical values of the chi-squared (χ^2) distribution for different numbers of degrees of freedom (k) and various significance levels (α). The first column shows the degrees of freedom, while the subsequent columns provide the corresponding critical values at selected probability thresholds (α = 0.01, 0.025, 0.05, 0.95, 0.975, 0.99). These values are used in hypothesis testing to determine whether the difference between observed and theoretical distributions is statistically significant. For instance, for k=16 and α=0.05, the critical value is 26.296 [7]. Since the computed value from Table 3 (χ^2 = 0.0816) is much smaller than this threshold, the hypothesis of conformity between empirical and theoretical fire occurrence distributions is accepted with high confidence.

3 CALCULATING THE VALUE OF STATISTICS

To verify the assumption about the probabilistic nature of the studied random variable, a statistical hypothesis testing procedure was applied. The goodness-of-fit of the empirical data to the assumed theoretical distribution was evaluated using the Pearson chi-square (χ^2) criterion.

The observed value of the chi-square statistic was calculated as

$$Z_N^2(\lambda) = 365 \cdot 0{,}081645166 = 29{,}8.$$

From Table 4 of critical points of the xi - square distribution with a degree of freedom *n-1-r=6* (*n=16*, the number of parameters soni *r=1*) using the table of critical points of the xi - square distribution, we find the critical limit for the case when the degree of freedom L=16, $t_{0,01}$ =29,8

So that, $Z_{16}^2(\lambda) = 29{,}8 < 32.000 = t_{0,01}$.

It follows from this inequality that the hypothesis that the random variable in question has a Poisson distribution can be accepted with an accuracy of α = 0.01.

Testing the hypothesis that the time spent on extinguishing a fire is an indicative distribution.

Regarding the city of Tashkent [8], based on the statistical data presented in the Table 5, we will test the hypothesis that the maintenance time of fire and rescue $\tau_{serv.}$ units in it has an exponential distribution of a random variable with an accuracy of α = 0.05 (Table 6).

Table 5: Service time intervals of fire and rescue units in Tashkent.

Interval №	Service time interval (hours)	Number of calls serviced m_i
1	0 – 0,25	1324
2	0,25 – 0,5	729
3	0,5 – 1	206
4	1–2	73
5	2-2,25	19
Total		2351

Table 6: Theoretical frequencies of serviced calls based on exponential distribution.

Interval №	1	2	3	4	5
$m_i^н$	1284,82	582,67	384,06	95,22	2,3

To solve the problem, we use the Pearson matching criterion.

1) We find the middle of each (ti-1 , ti) interval $\bar{t}_i$ and form the following Table 7.
2) Let's determine the average call service time τ_{aver} and the statistical value of the system's service intensity (μ) using the data from Tables 2 and 3 above.

$$\tau_{aver} = \frac{\sum_{i=1}^{4} \bar{t}_i m_i}{\sum_{i=1}^{4} m_i} = \frac{743{,}25}{2351} = 0{,}316142\ hours,$$

$$\mu = \frac{1}{\tau_{aver}} = \frac{1}{0{,}32} = 3{,}1631\ call/hours.$$

Table 7: Mean service time and empirical frequency distribution.

Interval №	1	2	3	4	5
$\bar{t}_i$	0,125	0,375	0,75	1,5	2,125
m_i(empirical frequency)	1324	729	206	73	19

3) Finding theoretical frequencies $m_i^н = nP_{i0}$:

$$m_i^{\text{н}} = nP_{i0} = 2351(e^{-3{,}1631 t_{i-1}} - e^{-3{,}1631 t_i}),$$
$$m_1^{\text{н}} = 2351(e^{-3{,}1631 \cdot 0} - e^{-3{,}1631 \cdot 0.25}) = 1284{,}82,$$
$$m_2^{\text{н}} = 2351(e^{-3{,}1631 \cdot 0.25} - e^{-3{,}1631 \cdot 0.5}) = 582{,}67,$$
$$m_3^{\text{н}} = 2351(e^{-3{,}1631 \cdot 0.5} - e^{-3{,}1631 \cdot 1}) = 384{,}06,$$
$$m_4^{\text{н}} = 2351(e^{-3{,}1631 \cdot 1} - e^{-3{,}1631 \cdot 2}) = 95{,}22,$$
$$m_5^{\text{н}} = 903(e^{-3{,}1631 \cdot 2} - e^{-3{,}1631 \cdot 2.25}) = 2{,}3.$$

4) Finding the observed value of the Pearson criterion:

$$Z_5^2(\mu) = \sum_{i=1}^{5} \frac{(m_i - m_i^{\text{н}})^2}{m_i^{\text{н}}} = 0{,}105121798,$$

5) Using the given degree of accuracy of the criterion *a = 0,99*, the degree of freedom was *n-1- r =6(n=5*, number of parameters *r* = -2) from the table of critical points of the xi-square distribution (Table 1) we find the critical limit

$$t_\alpha = \chi^2(0{,}05; 5)x = 0.554.$$

Thus, from the fact that 0,105121798<0.554 is equal to 0.554, the inequality $Z_5^2(\mu) < t_\alpha$. follows. Consequently, the time spent on eliminating fires can be considered an exponential distribution of the distribution law of a random variable with an accuracy of 0.99.

As a result of this research, optimization of the allocation and utilization of special equipment in fire and rescue units was achieved through the application of queuing theory. The optimization process included the expansion of the mathematical model by incorporating the number, type, and technical characteristics of the equipment, as well as response speed and recovery time. Statistical data from real incidents were analyzed, which allowed for the optimization of model calibration and improved accuracy of predictions. Several optimization scenarios were developed for different conditions - including urban areas, industrial facilities, and high-rise buildings - in order to determine the optimal number of units in each case. Furthermore, Optimization was enhanced by taking into account geographical factors such as unit location and transport accessibility, which corresponds to the international optimization frameworks described in [9]–[13].

A simulation model was constructed to optimize performance assessment under peak loads and emergency conditions. Finally, the obtained optimization results were validated through comparison with international experience, confirming the effectiveness of the proposed approach.

3 CONCLUSIONS

In conclusion, it can be said that the research successfully confirmed the validity of the underlying statistical hypotheses: the occurrence of emergency events follows a Poisson distribution ($\alpha = 0.01$), while both the service time of fire and rescue units in Tashkent ($\alpha = 0.05$) and the time required for extinguishing fires (accuracy 0.99) follow an exponential distribution. These results provided a solid mathematical foundation for applying queuing theory. On this basis, the study achieved its main goal - the optimization of the number and deployment of special equipment in fire and rescue units. The optimization ensured resource efficiency, reduced service time, and improved emergency response capacity. Given the rapid growth of high-rise construction and the associated rise in fire risks, the findings underline the urgent need for strategic planning and design work within the next 2–5 years. Overall, the results provide a scientifically grounded basis for the optimization of fire safety strategies in urban environments and confirm the effectiveness of the proposed methodological approach.

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