



DYNAMIC ASSESSMENT OF THE ADEQUACY OF FORCES AND RESOURCES FOR FIRE SUPPRESSION IN PUBLIC BUILDINGS AND FORECASTING THE RESOURCE-DEFICIT PERIOD

Sodiqov Alijon Nematulla Ugli

Doctor of Philosophy (PhD) in Technical Sciences, Associate Professor

Article history:	Abstract:
Received: 8 th July 2026 Accepted: 7 th August, 2026	The effectiveness of fire suppression in public buildings is determined not only by how quickly the first unit arrives, but also by the time at which the forces and resources required for a particular tactical scenario become fully available. Although current operational fire-fighting plans specify the required number of personnel and units and their arrival schedules, these two types of information are generally not integrated within a single dynamic criterion. The aim of this study is to develop a method for assessing the time-dependent adequacy of resources required for fire suppression in public buildings and for scenario-based forecasting of the resource-deficit period. Based on approved operational plans for six public facilities in the Samarkand and Tashkent garrisons, the following indicators were calculated: required resource R_{req}, cumulative available resource over time $R_{avail}(t)$, resource deficit $D(t)$, deficit window W, time to full requirement coverage t_{cov}, initial coverage coefficient K_0, and delay in full resource formation Δt_{form}. For scenarios with an explicitly specified requirement, t_{cov} ranged from 8.6 to 27 min. At the O-1 religious complex, although the first unit arrived in 2.5 min, the requirement of 24 personnel was fully met only at minute 27; at the O-3 hotel, an initial shortage of only one person prolonged the deficit period to minute 12. Within the garrisons, up to six identical units were found to recur in the plans for certain pairs of facilities, indicating that facility-level estimates may be optimistic under simultaneous multi-incident scenarios. The proposed approach quantitatively distinguishes between first-response time and the time required to assemble the full tactical resource and enables resource adequacy to be evaluated as a function of time in operational planning.
Keywords: fire and rescue forces; forces and resources; dynamic resource adequacy; resource deficit; deficit window; requirement coverage time; garrison resources	

1. INTRODUCTION

In fires occurring in public buildings, the effectiveness of operational forces and resources depends not only on their total number but also on the point in the incident development at which they become operational. Although the arrival time of the first unit is an important indicator for evaluating fire and rescue service performance, at large and complex facilities the complete tactical group required for fire suppression is formed through the staged arrival of several units. Therefore, “first-response time” and “time to full formation of the required resource” are not equivalent indicators.

The importance of the time factor has also been confirmed by recent research. Studies comparing actual and estimated response times have shown that planned times may systematically underestimate actual arrival times [14]. An empirical study published in Fire Safety Journal in 2025 reported that each additional minute of response time increases the probability of major damage and that the risk of total loss rises sharply after approximately 10–11 min [16]. These findings indicate that the time at which resources become fully operational has independent significance for preventive and operational planning.

International studies on fire and rescue resource allocation mainly address station-location optimization, station coverage, vehicle assignment, and response-time reduction [13]. Multi-vehicle response models have also shown that the arrival time of the last required crew needed to form a fully effective tactical group is a decisive parameter [15]. Research published in 2026 has proposed an extended “fulfilled response time” indicator that, in addition to the first-vehicle arrival time, accounts for delays in the arrival of the second and subsequent vehicles [17].

Nevertheless, two types of information contained in approved operational fire-fighting plans—the resource requirement calculated for a specific scenario and the sequence of unit arrivals—are generally not compared within a

unified time model. Consequently, the rapid arrival of the first unit does not necessarily mean that the facility is fully supplied with the forces and resources required. The scientific and methodological gap lies not in recalculating the final amount of resources, but in quantitatively expressing their adequacy over time and the period during which the requirement remains unmet.

The aim of the study is to develop a method for assessing the adequacy of forces and resources for public buildings and for scenario-based forecasting of the resource-deficit period on the basis of the dynamic balance between the scenario requirement specified in operational plans and the cumulative resources of arriving units over time. The scientific novelty is as follows: (1) first-arrival time is distinguished from the time to full requirement coverage; (2) resource shortage is expressed through $D(t)$, the deficit window W , and t_{cov} ; (3) the initial coverage coefficient K_0 and the delay in full resource formation Δt_{form} are introduced; and (4) recurrence of the same units in plans within a single garrison is formalized as a resource constraint for multi-incident scenarios.

2. MATERIALS AND METHODS

The study used the approved operational fire-fighting plans for six public facilities in the Samarkand and Tashkent garrisons and the corresponding tables of forces and resources [12]. The sample was formed not for statistical generalization, but to demonstrate the proposed calculation scheme under different deployment and facility conditions. For each unit, arrival time and the number of personnel in the operational crew were extracted and converted to a common time scale measured from the onset of the incident.

$$D(t) = R_{req} - R_{avail}(t); \quad W = \{t : D(t) > 0\}; \quad t_{cov} = \min\{t : R_{avail}(t) \geq R_{req}\} \quad (1)$$

where R_{req} is the personnel requirement calculated for a specific scenario in the operational plan, persons; $R_{avail}(t)$ is the cumulative personnel of units that have arrived by time t ; $D(t)$ is the resource deficit over time; W is the set of times for which $D(t) > 0$, i.e., the resource-deficit period; and t_{cov} is the first point in time at which the cumulative resource is no longer less than the requirement. In the numerical calculations, R_{req} was taken as equal to the scenario value specified in the plan and constant over time, whereas $R_{avail}(t)$ increases stepwise as units arrive.

$$K_0 = R_{avail}(t_{first}) / R_{req} \quad (2)$$

The initial coverage coefficient K_0 indicates the proportion of the scenario requirement covered when the first unit, or the first group arriving simultaneously, reaches the scene. $K_0 < 1$ indicates that the initial resource is insufficient; $K_0 = 1$ means that the requirement is fully covered; and $K_0 > 1$ means that the resource formed at the first stage already exceeds the plan requirement.

$$\Delta t_{form} = t_{cov} - t_{first} \quad (3)$$

Δt_{form} is the additional time elapsed after the arrival of the first forces until the full required resource has been assembled. Accordingly, t_{first} , K_0 , Δt_{form} , and t_{cov} were treated as complementary indicators of dynamic resource readiness.

$$M_{ij} = |B_i \cap B_j| \quad (4)$$

where B_i and B_j are the sets of units designated for deployment in the operational plans of facilities i and j within the same garrison, and M_{ij} is the number of units recurring in both plans. $M_{ij} > 0$ indicates that, in the case of two simultaneous incidents, the planned resource trajectories are not independent. In this study, M_{ij} was assessed as a structural constraint; dynamic reallocation under multiple incidents was not optimized because actual unit-occupancy and dispatch data were insufficient.

For the calculations, the incident onset was taken as $t=0$. Arrival times and personnel numbers were obtained from approved plans; actual traffic congestion, weather conditions, equipment failure, or a unit being engaged on another call were not included in the model. Therefore, t_{cov} is not a guaranteed time for a real incident, but a scenario-based forecast conditional on implementation of the deployment and mobilization scheme specified in the plan.

The requirement itself may change as the fire develops. However, because existing operational plans often provide the personnel requirement as a final scenario value, R_{req} was assumed to be constant in this study. This assumption defines the scope of the method: the result evaluates the temporal consistency between the resource requirement in the plan and the garrison's planned arrival sequence, rather than the dynamics of fire development itself.

Table 1

Initial response parameters of the study facilities

Facility type	Garrison	Arrival of the first unit
O-1 religious complex	Samarkand Region	2.5 min, 10 personnel
O-2 congress center	Samarkand Region	10 min, 20 personnel
O-3 hotel	Samarkand Region	5 min, 14 personnel
O-5 shopping and entertainment center	Tashkent City	4.2 min, 9 personnel
O-6 university academic building	Tashkent City	5 min, 15 personnel
O-7 market area	Tashkent City	7 min, 16 personnel

3. RESULTS

3.1. Time profiles of cumulative resources

The time profiles of cumulative personnel differed markedly among facilities in the Samarkand garrison. At the O-1 religious complex, the first resource of 10 personnel arrives at 2.5 min, but the next substantial increase in resources occurs at approximately minute 25, due to units located 18–30 km away. At the O-2 congress center, 20 personnel are assembled simultaneously at minute 10, whereas at the O-3 hotel, 14 personnel arrive within the first 5 min.

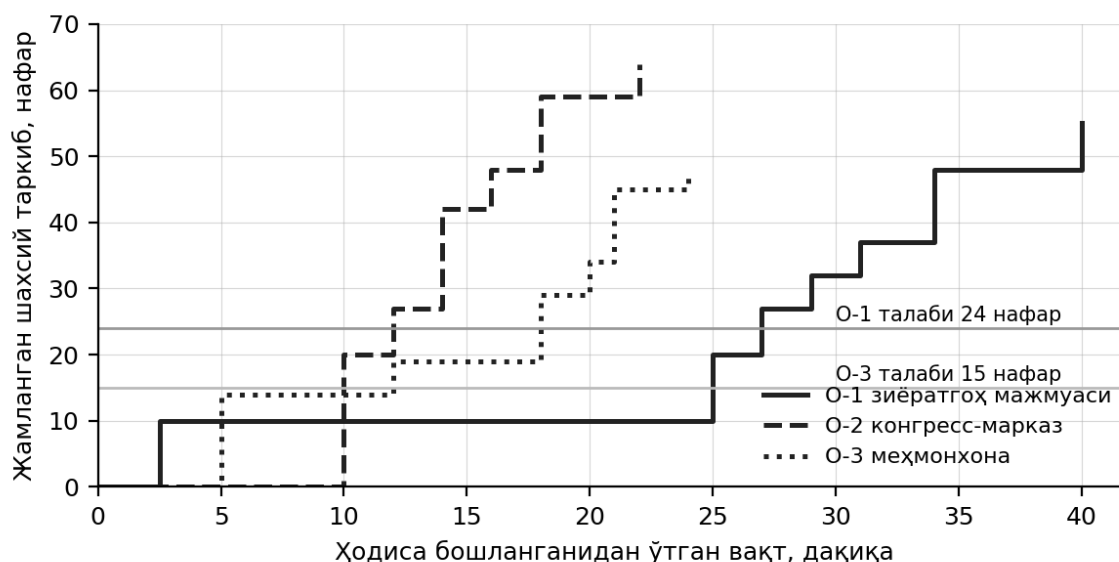


Figure 1. Change in cumulative personnel over time at facilities in the Samarkand garrison. Source: author's calculations based on data from [12].

In the Tashkent city garrison, resources accumulate more rapidly because of the relatively dense deployment pattern. At the O-5 shopping and entertainment center, 9 personnel are available at 4.2 min, 25 personnel by minute 5, and 36 personnel by minute 9. At the O-6 university academic building, 15 personnel are available at minute 5 and 25 by minute 8; at the O-7 market area, 16 personnel arrive within the first 7 min. Absolute numbers across garrisons should not be interpreted as an efficiency ranking; the principal criterion is the time at which the requirement of a specific scenario is fully covered.

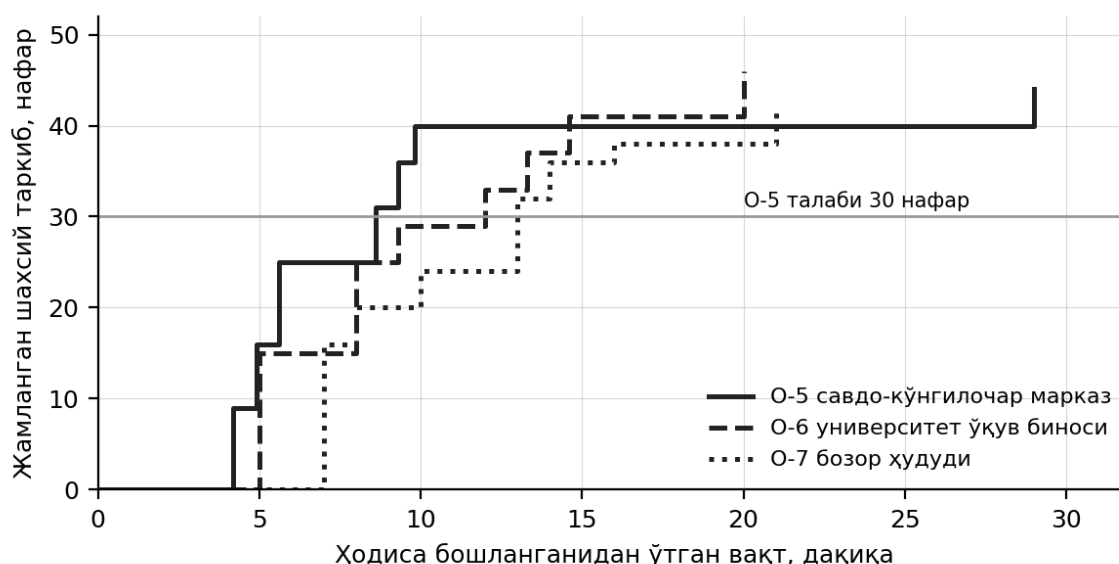


Figure 2. Change in cumulative personnel over time at facilities in the Tashkent city garrison. Source: author's calculations based on data from [12].

3.2. Deficit window and time to full requirement coverage

Using Eqs. (1)–(3), W , t_{cov} , K_0 , and Δt_{form} were determined for scenarios with a specified resource requirement. For the mosque scenario at the O-1 religious complex, $K_0=0.42$ and $\Delta t_{form}=24.5$ min; for the museum scenario, $K_0=0.50$ and $\Delta t_{form}=22.5$ min. For the O-2 congress center, $K_0=1.67$ in the first variant and $K_0=1.00$ in the second variant, with the requirement covered within the first 10 min in both cases. At the O-3 hotel, $K_0=0.93$ and $\Delta t_{form}=7$ min; at the O-5 shopping and entertainment center, $K_0=0.30$ and $\Delta t_{form}=4.4$ min.

Table 2

Indicators of resource-requirement coverage by scenario

Facility	Scenario	Plan requirement, personnel	Requirement coverage time, min	Deficit window
O-1 religious complex	mosque	24	27	0–27 min
O-1 religious complex	museum	20	25	0–25 min
O-2 congress center	first variant	12	10	0–10 min
O-2 congress center	second variant	20	10	0–10 min
O-3 hotel	plan calculation	15	12	0–12 min
O-5 shopping and entertainment center	plan calculation	30	8.6	0–8.6 min
O-6 university academic building	—	requirement not separately specified in the document	—	not calculated
O-7 market area	—	no calculation of forces and resources in the plan	—	not calculated

The O-3 hotel result clearly demonstrates the threshold sensitivity of dynamic assessment: 14 personnel arrive within the first 5 min, whereas the plan requirement is 15. Despite $K_0=0.93$, the remaining shortage of one person shifts t_{cov} to minute 12, when the next unit arrives. Thus, in a discrete resource system, even a small numerical difference near the requirement threshold can significantly affect the time to full tactical readiness.

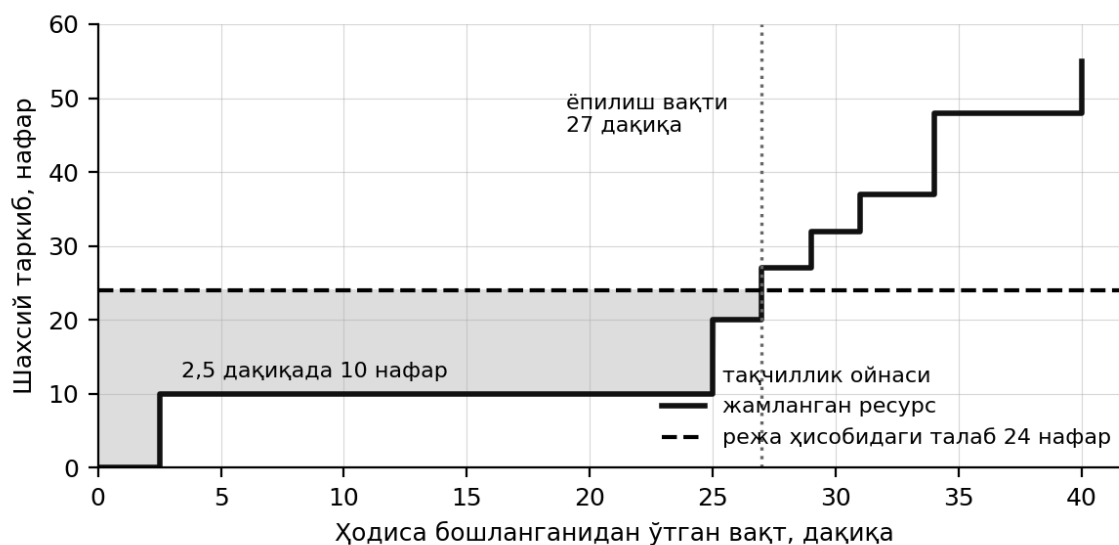


Figure 3. Coverage of the 24-person requirement and the 0–27 min deficit window for the mosque scenario at the O-1 religious complex. Source: author's calculations based on data from [12].

For the 24-person mosque scenario at the O-1 religious complex, the 27-min deficit period indicates that the facility's internal protection systems are particularly important during this interval. The plan lists 817 automatic detectors, 450 sprinklers in the basement, two underground water reserves of 300 m³ each, and 65 internal fire hydrants [12]. This result does not independently demonstrate the technical effectiveness of these systems; rather, it quantitatively identifies the critical interval until the external resource requirement is fully covered.

3.3. Resource overlap within the garrison

Using Eq. (4), the number of recurring units in the operational plans was calculated. In the Samarkand garrison, six units recur in the O-2 and O-3 plans, three in the O-1 and O-2 plans, and three units are common to all three facilities. In Tashkent, five units are common to the O-5 and O-6 plans, two to O-5 and O-7, and three to O-6 and O-7. This result shows that although facility plans are prepared separately, they are interdependent from the perspective of garrison resources.

Table 3

Recurring units in operational plans within the garrison

Garrison	Facilities	Number of recurring units
Samarkand	O-2 and O-3	6
Samarkand	O-1 and O-2	3

Samarkand	O-1, O-2 and O-3 (all three)	3
Tashkent	O-5 and O-6	5
Tashkent	O-5 and O-7	2
Tashkent	O-6 and O-7	3

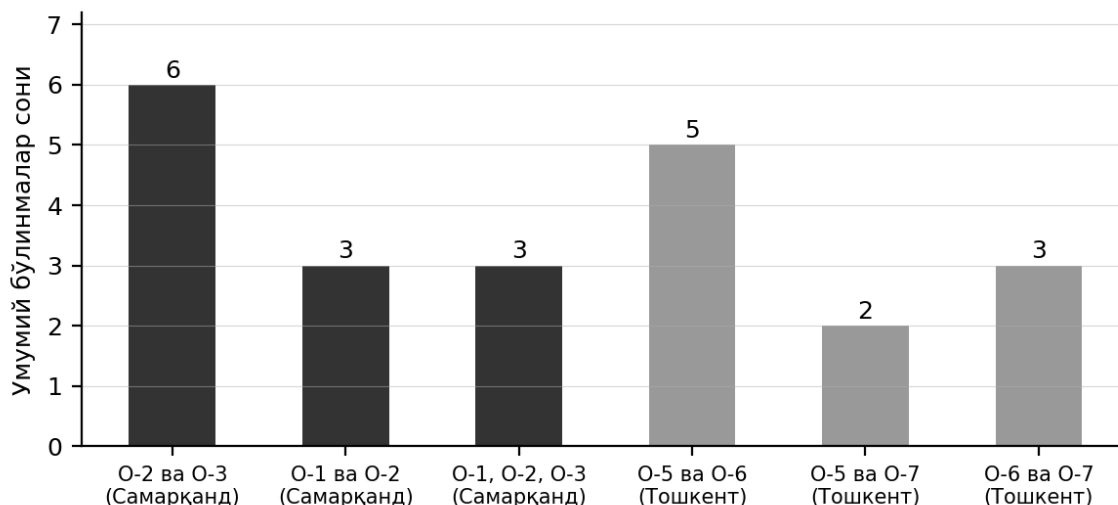


Figure 4. Number of recurring units in operational plans by facility pair. Source: author's analysis based on data from [12].

4. DISCUSSION

The main scientific implication of the results is that first-arrival time should not be equated with resource adequacy. International resource-allocation studies treat station location and first-response time as priority criteria [13, 14], but multi-crew response research has shown that the arrival time of subsequent resources needed to form a fully effective group is also decisive [15]. The present study extends this approach to the level of facility operational plans by distinguishing “time to full requirement coverage” as a separate indicator.

The indicators K_0 and Δt_{form} substantively complement W and t_{cov} . For example, although O-1 has the shortest first-response time—2.5 min—the initial resource in the mosque scenario covers only 42% of the requirement, and full formation requires an additional 24.5 min. Conversely, although the first arrival at the O-2 congress center occurs later, at 10 min, the first group itself fully covers the scenario requirement. Resource adequacy should therefore be interpreted as a function of time relative to the requirement, rather than merely as a “fast/slow arrival” assessment.

This conclusion is consistent with empirical findings from 2025 identifying a relationship between building fire damage and fire-service response time [16], as well as with extended response-time models published in 2026 that account for delays of subsequent vehicles in addition to the first vehicle [17]. However, the purpose of this study is not to optimize response time; rather, it forecasts when the existing resource trajectory will cover the scenario requirement if the approved plan is implemented. In this respect, W and t_{cov} are decision-support indicators for predefining a higher alarm level, substantiating the priority placed on the reliability of internal protection systems, and planning garrison reserves.

The recurrence of the same units in different facility plans within a garrison revealed an important system-level constraint. If two incidents occur simultaneously, shared resources for which $M_{ij} > 0$ cannot be counted in full for both facilities at the same time. Therefore, W calculated under the single-incident assumption remains an optimistic estimate. At the next stage, a dynamic resource balance should be developed that accounts for the garrison's current occupancy status, duty roster, uncertainty in travel time, and multi-incident calls.

4.1. Study limitations

The study has several limitations. First, arrival times and personnel numbers are planned data taken from approved operational plans and do not reflect actual traffic congestion, weather, or unit occupancy during a real incident; international studies show that systematic differences may exist between planned and actual response times [14]. Second, R_{req} was assumed to be constant over time, and changes in demand as the fire develops were not modeled. Third, because the requirement is not separately specified for O-6 and the O-7 plan contains no calculation of forces and resources, W , K_0 , and t_{cov} were not numerically evaluated for these facilities. Fourth, six facilities are insufficient for statistical generalization. The results should therefore be regarded as a case-based verification of the calculation method using real operational documents; subsequent validation against actual incident logs is required.

5. CONCLUSION

1. A dynamic calculation scheme was developed for assessing resource adequacy for fire suppression in public buildings that is not limited to the arrival time of the first unit; resource shortage is expressed through $D(t)$, the deficit window W , and the time to full requirement coverage t_{cov} .

2. The initial coverage coefficient K_0 and the delay in full resource formation Δt_{form} were introduced. For scenarios with an explicitly specified requirement, t_{cov} ranged from 8.6 to 27 min; for the O-1 mosque scenario, $K_0=0.42$ and $\Delta t_{\text{form}}=24.5$ min, while for O-5, $K_0=0.30$ and $\Delta t_{\text{form}}=4.4$ min.
3. At the O-3 hotel, although the initial resource of 14 personnel corresponded to $K_0=0.93$ relative to the requirement of 15 personnel, the shortage of one person extended t_{cov} to 12 min. This demonstrates the high sensitivity of full tactical readiness time to the requirement threshold in a discrete resource system.
4. Up to six identical units were found to recur in plans for different facilities within the same garrison. Therefore, facility-level resource-adequacy estimates are valid only for a single-incident scenario; under multi-incident conditions, the occupancy of shared units must be accounted for separately.
5. The proposed approach integrates the "scenario requirement" and "unit arrival schedule" data that are dispersed across operational plans into a unified time model. Its practical significance lies in identifying in advance the critical resource-deficit period that persists until external forces are fully assembled and in supporting decisions on mobilizing additional forces and prioritizing internal protection systems.

REFERENCES

1. Law of the Republic of Uzbekistan No. ZRU-226 of 30 September 2009 "On Fire Safety."
2. Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 649 of 20 October 2020 "On Approval of Fire Safety Rules."
3. SHNQ 2.01.02-04. Fire Safety of Buildings and Structures. Tashkent: Ministry of Construction of the Republic of Uzbekistan, 2004.
4. SHNQ 2.08.02-23. Public Buildings and Structures. Tashkent.
5. Ivannikov V.P., Klyus P.P. Handbook for the Fire Suppression Commander. Moscow: Stroyizdat, 1987. [in Russian].
6. GOST 12.1.004-91. Occupational Safety Standards System. Fire Safety. General Requirements. Appendix 2.
7. Hurley M.J. et al. (eds.). SFPE Handbook of Fire Protection Engineering. 5th ed. New York: Springer, 2016.
8. Predtechenskii V.M., Milinskii A.I. Planning for Foot Traffic Flow in Buildings. New Delhi: Amerind Publishing, 1978.
9. Kuligowski E.D., Peacock R.D., Hoskins B.L. A Review of Building Evacuation Models. 2nd ed. NIST Technical Note 1680. Gaithersburg: NIST, 2010.
10. ISO 16730-1:2015. Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General.
11. Convention on the Rights of Persons with Disabilities, Article 11.
12. Approved operational fire-fighting plans for the study facilities and their tables of forces and resources. Samarkand and Tashkent garrisons, 2020–2026. Service documents.
13. Eslamzadeh M.K., Grilo A., Espadinha-Cruz P. A Framework for Resource Allocation in Fire Departments: A Structured Literature Review. *Fire*. 2022;5(4):109. <https://doi.org/10.3390/fire5040109>
14. Hassler J., Andersson Granberg T., Ceccato V. Socio-spatial Inequities of Fire and Rescue Services in Sweden: An Analysis of Real and Estimated Response Times. *Fire Technology*. 2024;60:193–212. <https://doi.org/10.1007/s10694-023-01496-3>
15. Zhou Y., Liu H., Wang N., Gu Y. Lagrangian relaxation-based approaches for cooperative location and assignment of emergency responders. *Alexandria Engineering Journal*. 2024;107:225–234. <https://doi.org/10.1016/j.aej.2024.07.030>
16. Montagna G.M., van den Berg P.L., Oskam V., Jagtenberg C.J., Oosterveen V., van der Mei R.D., Klooster J. Effect of fire department response time on fire damage in the Netherlands. *Fire Safety Journal*. 2025;157:104517. <https://doi.org/10.1016/j.firesaf.2025.104517>
17. Amirdadi M., Mohammadi A., Park P.Y., Nourinejad M., Solis A.O. A GIS-based queuing location-allocation and robust optimization framework for urban fire emergency response. *Safety Science*. 2026;203:107327. <https://doi.org/10.1016/j.ssci.2026.107327>