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Chemical, biological and radiological reconnaissance process of potentially dangerous objects as a queueing theory with priorities

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Abstract. The relevance of the study is due to the fact that according to the experience of the Russia-Ukraine war, during combat actions in urbanized areas, chemical, biological and radiological reconnaissance is of particular importance due to the fact that the destruction (accidents) at potentially dangerous facilities can lead to a complex nuclear, biological and chemical situation that will negatively affect troops. This requires a presentation of the chemical, biological and radiological reconnaissance process due to such characteristics that will allow to assess the effectiveness of its conduct in a complicated chemical, biological and radiological situation. In this regard, the article presents one of the approaches to present the process of chemical, biological and radiological reconnaissance of potentially hazardous objects as a queueing theory with priorities. The leading approach in the presented process is the employment of such characteristics as the intensity of receiving and servicing requests for chemical, biological and radiological reconnaissance, their average number, the average waiting time for an arbitrarily selected request, and the average length of the request queue. In the process of chemical, biological and radiological reconnaissance as a queueing theory with priorities, the distributions of the duration of servicing requests for chemical, biological and radiological reconnaissance activities are the same for the requirements of all priority categories, and the distributions of the duration of servicing these requests in all channels are exponential with average service speeds. The article describes the characteristics of the chemical, biological and radiological reconnaissance process, which depends on the number of reconnaissance objects and their priority during combat actions in urbanized areas and the number and capabilities of chemical, biological and radiological intelligence technical means involved in the execution of tasks. The materials of the article will be interesting for officials of military command and control bodies who plan chemical, biological, and radiological reconnaissance during combat actions, especially in urbanized areas.

Keywords: urbanized areas, intensity, request, channel.

Introduction

In the context of the full-scale invasion of the armed forces of russian federation (RF armed forces), which has been ongoing since February 24, 2022, there are potential chemical, biological, radiological and nuclear (CBRN) threats that could result in significant losses for the Armed Forces of Ukraine (AFU). These threats are reflected in the guiding documents (Instruction on the Functioning of the System of Prevention and Warning of Chemical, Biological, Radiological and Nuclear Threats (incidents) in the system of the Ministry of Defense of Ukraine, 2023) and require strengthening the capabilities of the Armed Forces of Ukraine to protect against these threats in accordance with the decrees of the President of Ukraine (National Security Strategy of Ukraine, 2020), (Military Security Strategy of Ukraine, 2021), (Strategic Defense Bulletin of Ukraine, 2021).

Today, there is an increase in the level of CBRN threats as a result of combat actions in urbanized areas of cities and large industrial agglomerations due to their saturation with a large number of potentially dangerous objects (PDOs), in particular, nuclear power, chemical and oil refining industries, whose destruction (accidents) can lead to a complex chemical, biological, radiation (CBR) situation (Military and Historical Description of the russia-Ukraine War, 2023), which will negatively affect troops (Methodology for Assessing the Situation in Man-Made and Natural Emergencies, 2018).

Combat actions near the Chornobyl and Zaporizhzhia nuclear power plants in 2022 are the relevant examples of this, damage to sections of the Togliatti-Odesa ammonia pipeline, and incidents involving the leakage of highly toxic substances as a result of damage to chemical industry facilities in Donetsk region. In addition, of particular concern are the repeated attempts by the russian armed forces to use chemical warfare agents and the constant threats by some russian officials to use nuclear weapons against the Armed Forces of Ukraine (Zaluzhnyi, Moisiuk, Shaptala, 2022).

This demonstrates the relevance and importance of troops support, which is carried out to create favorable conditions for successful preparation and conduct of combat operations, and to ensure the performance of assigned tasks (Lessons of the russia-Ukraine War of 2022: military factors, 2022). An important component of troops support is their CBRN protection. CBRN protection of troops is a set of activities to plan and execute tasks aimed at minimizing troop losses during operations under CBR contamination. One of the CBRN protection important tasks is the CBR reconnaissance activities implementation (Doctrine on Chemical, Biological, Radiological and Nuclear Protection of Troops (Forces), 2020).

CBR reconnaissance is organized and carried out with the purpose of timely detection of CBR contamination at control points, routes of deployment, supply routes, evacuation routes, in the areas of troops' concentration and operation for their notification. It is carried out by regular and specially trained non-staff CBR reconnaissance units, personnel of the operational duty service of military command and control bodies by collecting data on CBR situation on the routes of movement, areas and directions of troops' operations (Marushchenko, Haidabuka, Halak, 2010).

Despite the possible scale of the consequences of CBRN threats and unfavourable situation for the troops, the capabilities of the Armed Forces of Ukraine to conduct CBR reconnaissance are still limited. This affects the timeliness of detecting and assessing CBR contamination and does not allow military command and control bodies of various levels to make necessary operational decisions in a timely manner. Thus, it is obvious that CBR reconnaissance of the PDO in modern warfare conditions in urbanized areas is of particular importance.

Therefore, in order to enhance the Armed Forces of Ukraine capabilities for CBRN protection of troops, there is a need to present the CBRN reconnaissance process as a set of sequential actions aimed at timely detection of CBRN contamination at the PDO. For this purpose, it is proposed to present the CBR reconnaissance process as queueing theory, which has such characteristics as the intensity of receiving and servicing requests for reconnaissance, their average number, the average waiting time for an arbitrarily selected request and the average length of the request queue, which

will allow to assess the effectiveness of CBR reconnaissance of the PDO, especially in a complicated CBR situation.

Materials and Methods

By its nature, CBRN missions are aimed at protecting troops during combat operations in urbanized areas, in particular performing PDO CBR reconnaissance activities, is to serve a random flow of requests with a certain priority. Therefore, to represent the process of these activities, it is proposed to apply the queueing theory model with priorities ($_{Mi/M/s}$):($NPRP/\infty/\infty$), (Taha, 1985). In this model, it is assumed that several queues are formed before the maintenance section of requests for CBR reconnaissance of the PDO, in each of which the requests have a certain level of relative priority. The first queue of these requests has the highest priority, and the last one has the lowest priority. The initiated procedure for servicing requests for PDO CBR reconnaissance activities is brought to an end.

In addition, in this model, the distributions of the duration of servicing requests for CBR reconnaissance activities are the same for the requirements of all priority categories of the PDO, and the distributions of the duration of servicing these requests in all service channels are exponential with average service speeds. The service channel is defined as a technical means (TM) intended for CBR reconnaissance activities. Receiving requests of the appropriate priority for PDO CBR reconnaissance activities is distributed in time in accordance with the Poisson law and is characterized by the average frequency of receipt.

The PDO CBR reconnaissance process as a queueing theory with priorities ($_{Mi}$ / *M* / *s*):($NPRP/\infty/\infty$) is characterized by the following indicators:

$_{Mi}$ is the Poisson law of distribution of the time of receipt of requests for CBR reconnaissance activities in the *i-th* queue ($i = 1, 2, ... j$);

M is the Poisson law of distribution of the time of servicing requests for CBR reconnaissance activities;

n is *the* number of service channels (CBR reconnaissance tasks);

NPRP is a service discipline that stipulates that CBR will be conducted without interruption (a system with relative priority);

the number of applications in the system and the capacity of the application source are not limited.

The PDO CBR reconnaissance process as a queueing theory with priorities is shown in Figure 1.

It is proposed to calculate the characteristics of the PDO CBR reconnaissance process as a queueing theory with priorities and to assess the effectiveness of CBR reconnaissance in three stages.

At the first stage, the priority of CBRN reconnaissance objects is determined by their importance during combat actions in urbanized areas.

For this purpose, the factors that influence the prioritization of these objects on the basis of their importance are determined, namely:

the degree of CBR reconnaissance objects importance;

the degree of CBR reconnaissance objects importance on the basis of the importance of military subsystems, in whose interests they are used;

the degree of CBR reconnaissance objects importance for the CBRN troops protection system.

Further, using the identified factors, a scale of pairwise comparisons is selected to assess the CBR reconnaissance objects importance, in particular, PDO, during combat operations in urbanized areas, for which a calculation model of expert evaluation of hierarchical structures is developed (Velychko, Kolomiiets, Hordienko, Shevtsov, Karpenko, Haber, 2015).

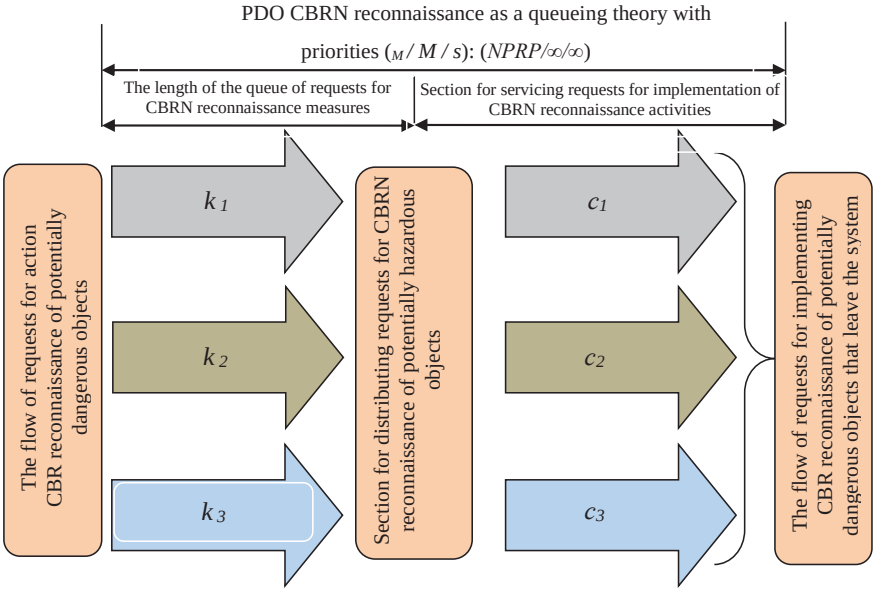


Figure 1. PDO CBR reconnaissance process as a queueing theory with priorities

Notes: k_1 - request with the highest priority; k_2 - request with medium priority; k_3 - request with the lowest priority; $_{c1}$, $_{c2}$, $c3$- service **channels**.
Source: developed by the authors on the basis of queueing theory research (Taha, 1985).

As a result of the comparison of the selected factors and alternatives, balanced inversely symmetric eigenvector evaluation matrices are formed for all rows in the comparison matrices of the identified factors and alternatives. After checking the numerical and ordinal consistency of the filled-in matrices and determining the indices of their consistency, the CBR reconnaissance objects' priority during combat actions in urbanized areas is distributed according to Harrington's "scale of desirability" (Shutiak, 2020).

The CBR reconnaissance objects prioritisation according to Harrington's "scale of desirability" is shown in Table 1.

Table 1. The CBRN reconnaissance objects prioritisation according to Harrington's "scale of desirability"

Harrington's scale of desirability	CBRN reconnaissance objects prioritisation
1,0–0,81	Highest priority (excellent level)
0,80–0,31	Medium priority (good and satisfactory)
0,30–0	Lowest priority (lower level)

Source: developed by the authors on the basis of research on the distribution of priorities (Shutiak, 2020)

At the second stage, the following characteristics of the performing CBR reconnaissance activities process during combat actions in urbanized areas are consistently determined, such as the intensity of receipt and servicing of requests for CBR reconnaissance activities of the PDO with the *k-th* priority, *units/day*:

$$\lambda_1 = \frac{q_{k1}}{T}; \lambda_2 = \frac{q_{k2}}{T}; \lambda_3 = \frac{q_{k3}}{T}; \mu = \frac{t_{r3}}{t_p}, \quad (1)$$

where $\lambda_{1(2,3)}$ is the intensity of receipt of requests for CBRN reconnaissance activities of the PDO with the *k-th* priority,

units/day; μ - is the intensity of servicing requests for CBRN reconnaissance activities of the PDO,

units/day; $q_{k1(k2,k3)}$ - the number of CBRN reconnaissance objects with the *k-th* priority during *T* days of combat of combat operations, units*;*

t_{T3} - average time of productive operation of CBRN reconnaissance vehicles during the day, *hours/day*;

t_p - is the average reconnaissance time of one PDO, *hours;*

T - duration of combat operations, *days*.

Employing (1), we calculate the average number of requests for CBRN reconnaissance activities of the *k-th* priority that are received during the service of one request *with* service channels, units*:*

$$S_1 = \frac{\lambda_1}{c \cdot \mu};\ S_2 = S_1 + \frac{\lambda_2}{c \cdot \mu};\ S_3 = S_2 + \frac{\lambda_3}{c \cdot \mu}, \tag{2}$$

Where c is the number of vehicles engaged in CBR reconnaissance activities, *units.*

After that, the relative reduced intensity of requests for PDO CBR reconnaissance activities the is determined:

$$\rho = \frac{\lambda_n}{\mu}, \tag{3}$$

where $\lambda_n = \lambda_1 + \lambda_2 + \lambda_3$.

Employing the initial data and the indicators calculated in (1) and (3), the average value of the exponential distribution is calculated:

$$E = \frac{1}{\mu \cdot c\left[\rho^{-c} \cdot (c-\rho) \cdot (c-1)! \sum_{n=0}^{c-1} \frac{\rho^n}{n!} + 1\right]}. \tag{4}$$

Next, we calculate the average waiting time for PDO CBR reconnaissance activities of each priority, in *days*:

$$Y_1 = \frac{E}{(1-S_1)},\ Y_2 = \frac{E}{(1-S_1)\cdot(1-S_2)},\ Y_3 = \frac{E}{(1-S_2)\cdot(1-S_3)}. \tag{5}$$

After that, the average waiting time for an arbitrarily selected request for PDO CBR reconnaissance activities is determined, in *days*:

$$Y' = \left(\frac{\lambda_1}{\lambda_n}\right) \cdot Y_1 + \left(\frac{\lambda_2}{\lambda_n}\right) \cdot Y_2 + \left(\frac{\lambda_3}{\lambda_n}\right) \cdot Y_3. \tag{6}$$

Next, we calculate the average length of the queue of requests for PDO CBR reconnaissance, units:

$$L_q = \lambda_n \cdot Y'. \tag{7}$$

At the third stage, the effectiveness of PDO CBR reconnaissance is assessed according to the following condition:

$$L_q \le L_0, \tag{8}$$

where $L0$ is the maximum number of requests in the queue for PDO CBR reconnaissance, *units*.

If the accepted condition is met, PDO CBR reconnaissance is considered to be effective.

As an example, consider one of the options for calculating the characteristics of the PDO CBR reconnaissance process as a queueing theory with priorities and assessing the CBR reconnaissance effectiveness.

Initial data:

CBRN reconnaissance objects number - 150 *units*;

combat actions duration (T) - 10 *days*;

average time of productive operation of CBR reconnaissance vehicles during a day ($tPro$) - 10 *hours/day*;

average time of reconnaissance of one PDO by CBR reconnaissance vehicles (tr) - 1 *hour;*

CBR vehicles number engaged in CBR activities (s) - 2 *units;*

the maximum number of requests in the queue for the PDO CBR reconnaissance activities implementation ($L0$) - 10 *units*.

Under such conditions, the procedure for calculating the characteristics of the PDO CBR process as a priority-based queueing theory and assessing the CBR reconnaissance effectiveness is as follows:

1. Employing the initial data, we prioritize CBR reconnaissance objects according to their importance during combat actions in urbanized areas:

highest priority ($qk1$) - 20 *units;*

medium priority ($qk2$) - 50 *units;*

lowest priority ($qk3$) - 80 *units*.

2. Using (1), we determine the intensity of receipt (λ) and service (μ) of requests for PDO CBR reconnaissance activities with the *kth* priority:

the request receipt intensity for PDO CBR reconnaissance activities of the highest priority ($qk1$) - $\lambda 1 = 2$ *units/day*;

the requests intensity for PDO CBR reconnaissance activities of the medium priority ($qk2$) - $\lambda 2 = 5$ *units/day*;

the requests intensity for PDO CBR reconnaissance activities of the lowest priority ($qk3$) - $\lambda 2 = 8$ *units/day*;

servicing requests intensity for PDO CBR reconnaissance activities - $\mu = 10$ *units/day*.

3. Employing (2), we calculate the average number of requests (S) for CBR reconnaissance activities of the *k-th* priority that are received during the service of one request *with* service channels:

the requests average number for PDO CBR reconnaissance activities of the highest priority - $S1 = 0.1$ *units;*

the requests average number for PDO CBR reconnaissance activities of the medium priority - $S2 = 0.35$ *units;*

the average number of requests for PDO CBR reconnaissance activities of the lowest priority - $S3 = 0.75$ *units*.

4. Equation (3) is used to determine the relative reduced intensity of requests (ρ) for PDO CBR reconnaissance activities: $\rho = 1{,}5$.

5. Using equation (4), we calculate the mean value of the exponential distribution: $E = 0{,}065$.

6. Using (5), we calculate the average waiting time (Y) for PDO CBR reconnaissance activities implementation of each priority:

the average waiting time for PDO CBR reconnaissance activities implementation of the highest priority is $y1 = 0.072$ *days*;

the average waiting time for PDO CBR reconnaissance activities implementation of the medium priority is $y2 = 0.111$ *days*;

the average waiting time for PDO CBR reconnaissance activities of the lowest priority is $_{Y3}$ = 0.393 *days*.

7. Using (6), we determine the average waiting time for an arbitrarily selected request (*Y'*) for PDO CBR reconnaissance activities: *Y'* = 0.26 *days*.

8. Using (7), we calculate the average length of the queue of requests ($_{Lq}$) for PDO CBR reconnaissance activities implementation: $Lq_{=}$ 4 *units*.

9. We compare the received in a paragraph 8 result of the requests queue average length calculation (L_q) for PDO CBR reconnaissance activities realisation with the maximum number of these requests (L_0) assumed in the initial data and conclude that PDO CBRN reconnaissance implementation under the given conditions of the situation is effective.

Results and Discussions

Thus, by calculating of the PDO CBR reconnaissance process characteristics as a queueing theory with priorities, in particular, the intensity of receiving and servicing requests for CBR reconnaissance activities of a certain priority, the average number of requests for these activities, the relative reduced intensity of receiving requests, the average waiting time for CBRN reconnaissance activities of a certain and arbitrarily selected priority, the average length of the queue of requests for these activities, the PDO CBR reconnaissance effectiveness was assessed.

This assessment shows that the calculating results of the PDO CBR reconnaissance process characteristics as a prioritised queueing theory depends on the factors that influence the PDO prioritisation by their importance during combat operations in urbanised areas, the CBR reconnaissance objects number and the CBR reconnaissance assets' number and capabilities involved in the tasks execution. The analysis of studies and publications showed that issues related to the troops' CBRN protection process, in particular CBR reconnaissance, have been addressed in a number of works. For example, the general issues of CBR reconnaissance organisation and performance (Radiation, Chemical, Biological Protection of Units, 2007), tactics of radiation, chemical, biological protection troops in relation to the CBRN reconnaissance activities execution (Shvets, Marushchenko, Koval, 2008), tactical calculations substantiation for CBRN protection tasks and activities, in particular CBR reconnaissance activities (Hutchenko, Hyshko, Prokofiev, 2017). However, the PDO CBR reconnaissance process as a queueing theory with priorities was not considered in these studies and publications. The russia-Ukraine war experience convinces us that during the conduct of combat actions in urbanised areas with a PDO large number, the volume of CBR reconnaissance activities will increase and the priorities for their performance will change. This requires consideration of the CBR reconnaissance process through such characteristics that will allow to assess the effectiveness of its conduct in a CBR-complicated environment, which was done in the article with the help of the studied queueing theory with priorities (Taha, 1985).

Conclusion

In this manner, the above dependencies make it possible to present the PDO CBR reconnaissance process through the receipt intensity and requests servicing for the CBR reconnaissance activities, the requests average number of the *k-th* priority received by the service channel, the average waiting time for an arbitrarily selected request for the performance of these objects' activities of the *k-th* priority and the request queue average length, which allows to assess the PDO CBR reconnaissance effectiveness, especially in a complicated CBR situation. The research has shown that these indicators mainly depend on the PDO's number and priority, the CBR reconnaissance vehicles' number and capabilities. One of the advantages of the considered approach is that when presenting the PDO CBRN reconnaissance process as the queueing theory with priorities,

the degree of reconnaissance importance objects for the military and the CBR security system is taken into account.

Prospects for further research in this area are to consider the processes of other CBRN protection activities for troops, considering the loss of CBRN assets and possibilities for their recovery during combat operations in urbanised areas.

Recommendations

The materials of the publication will be of interest to military command and control bodies who are planning the CBRN troops protection including CBR reconnaissance during combat operations in urbanised areas. The results of these calculations will allow assessing the PDO CBR reconnaissance effectiveness in the CBR complicated environment.

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