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# Improved Methodological Approach to Forming the Structure and Composition of the Repair System for Armament, Military and Special Equipment in the Armed Forces of Ukraine

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**Abstract.** The article is devoted to improving the methodological approach to forming the structure and composition of the repair system for armament, military and special equipment based on the use of queueing system theory, taking into account the specific features of modern combat operations. Experience in repelling the armed aggression of the russian federation convincingly demonstrates that the production capabilities of the repair system are insufficient for the timely performance of tasks related to the repair of damaged items of armament, military and special equipment. An analysis of the repair system for armament, military and special equipment under

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combat conditions shows that the structure and composition of repair bodies do not meet current requirements. Therefore, the repair system for armament, military and special equipment in the Armed Forces of Ukraine requires more detailed consideration. For this purpose, the repair system model may be represented as a queueing network. In this network, some links should be represented as multichannel queueing systems with unreliable or degrading channels. The aim of the article is to improve the methodological approach to forming the structure and composition of the repair system for armament, military and special equipment on the basis of a queueing network, taking into account the specific features of modern combat operations. The methodological basis of the research consists of the combined use of queueing theory, probability theory, system modelling, comparative analysis and analytical generalisation to represent repair units as elements of a queueing network with unreliable and stochastic degrading service channels. The scientific novelty consists in representing repair subunits as multichannel queueing systems in which several channels are unreliable or degrading, which makes it possible to determine the structure and composition of repair subunits more accurately and objectively. The improved methodological approach makes it possible to determine the parameters of repair subunits in advance and on a substantiated basis when forming the structure and composition of the repair system for armament, military and special equipment.

**Keywords**: repair system; armament, military and special equipment; AMSE; queueing system; queueing network; unreliable channels; degrading channels; repair units; intensity of combat operations.

## Introduction

Based on the analysis of losses of armament, military and special equipment (AMSE) of the Armed Forces of Ukraine during modern combat operations, it can be concluded that the nature and structure of these losses require the effective employment of repair units and subunits [1], [2]. However, an analysis of the AMSE repair system demonstrates that the capabilities of the repair system are insufficient [2]. Above all, this concerns the production capabilities of repair and recovery units and subunits. Experience shows that they are insufficient for the timely performance of tasks related to the repair of damaged AMSE items.

According to the daily information bulletins of the Logistics Forces Command [1] regarding AMSE recovery, the insufficient number of repair subunits, their composition, manning level, and the physical and psychological condition of specialists, caused by age and chronic diseases, have a negative impact on the promptness of AMSE recovery. The consequence of this situation is the untimely performance of repairs and delays in the delivery of recovered AMSE, which reduces the level of provision and combat capability of units and subunits. For this reason, the repair system requires improvement; therefore, it is necessary to determine a research direction for the formation of an adequate methodological apparatus. Consequently, the development of a correct and adequate model of the AMSE repair system during modern combat operations, as well as the determination of the structure and composition of the repair system and its subsystems, constitutes a relevant scientific task. The aim of the article is to improve the methodological approach to forming the structure and composition of the AMSE repair system on the basis of queueing network models, taking into account the unreliability and stochastic degradation of service channels under modern combat conditions. To achieve this aim, the article analyses existing approaches to modelling AMSE repair processes, substantiates the representation of repair subunits as multichannel queueing systems, considers unreliable and stochastic degrading service channels, and demonstrates the practical applicability of the proposed approach through illustrative calculations.

## Literature Review

Having analysed recent studies and publications on this subject, the authors established that

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approaches to improving the repair system for AMSE items with damage and failures have passed through several stages. At the first stage, modelling was carried out using mathematical methods based on the hypothesis of a linear relationship between the number of repair bodies, their composition and indicators, and the effectiveness of the repair process [3].

At the second stage, stochastic models of the repair process were presented. They were based on probability theory, queueing theory and statistical observations, while the repair system itself was represented as a queueing system (QS) [4]–[7].

However, it should be noted that open scientific sources in Ukraine contain no publications on studies of scenarios in which QS with unreliable channels and QS with degrading channels are considered.

**Methodological Framework**

The methodological framework of the research is based on a system approach to modelling the AMSE repair system as a queueing network. The study applies the mathematical apparatus of queueing theory, probability theory and stochastic modelling to describe the functioning of repair units under conditions of channel unreliability and degradation. Comparative analysis is used to identify the limitations of previously proposed deterministic approaches, while analytical generalisation is applied to substantiate the improved methodological apparatus. To form models of the repair system, the mathematical apparatus of queueing theory is most often used. This apparatus makes it possible to form adequate models based either on a queueing system (QS) or on a queueing network (QN). For example, in [3] a methodological approach based on the QN apparatus was proposed; however, it provided for the use of correction coefficients that took into account a decrease in the production capacities of repair subunits and the work capacity of a worker during a work shift in the course of combat operations. The drawback of this approach lies in the use of rather subjective indicators. In addition, these indicators are explicitly deterministic, which does not constitute an adequate model of the real process. Therefore, the methodological apparatus developed in [3] requires improvement.

The essence of the proposed improved methodological apparatus is as follows.

A repair unit (subunit) is represented as a queueing network consisting of a certain number of QS nodes, with each QS generally being multichannel. The specific feature of the improved approach is that it considers not only so-called classical multichannel QS (*M/M/n*), but also multichannel QS that may have:

– one or several unreliable channels;

– one or several stochastic degrading channels.

Thus, a repair subunit should be represented as a multichannel QS in which some channels are unreliable, while some serviceable channels are degrading.

Multichannel QS with unreliable servers constitute a model in which service channels may randomly fail and be restored. Such systems describe the operation of technical, production and other processes more realistically.

Multichannel QS with stochastic degrading channels constitute a model in which channels do not fail completely, that is, they do not transition to an inoperable state, but randomly degrade, reducing the recovery intensity for damaged or non-operational AMSE.

A model of a repair subunit with a QS containing unreliable and/or degrading channels may be described as follows:

– the input flow is Poisson, with an arrival intensity of service requests $\lambda$;

– the QS contains $n$ service channels;

– each channel may contain $m$ subchannels;

– a channel is in normal condition with probability $p$ and degrades with probability $1 - p$.

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**Results and Discussions**

**1. Multichannel QS with Unreliable Channels**

The unreliability of channels in a multichannel QS leads to such negative consequences as an increase in the queue of requests in the system, an increase in the waiting time of requests for service, and a possible loss of system stability.

When considering this category of QS, it should first be specified that two random processes are added to multichannel *M/M/n* QS with unreliable channels:

– each channel may fail with intensity $\alpha$ (channel failure with intensity $\alpha$);

– each channel is restored with intensity $\beta$ (channel restoration with intensity $\beta$).

Thus, a channel may be in two states: operational or inoperable (service is not provided).

To evaluate such a system, the shares of channel operating time should be determined. The share of time during which a channel operates depends on its failures and restorations. If the failure intensity $\alpha$ and restoration intensity $\beta$ are the same for each channel, then the share of time during which the channel operates is:

$$P_{operates} = \frac{\beta}{\alpha+\beta}.$$

Since each channel may be faulty, the effective service intensity for each channel will be reduced in proportion to the time during which the channel is operational:

$$\mu_{eff} = \mu \cdot \frac{\beta}{\alpha+\beta}.$$

Thus, the effective service intensity for all $n$ channels is:

$$M_{eff} = n \cdot \mu \cdot \frac{\beta}{\alpha+\beta},$$

where $n$ is the number of channels in the QS.

The main characteristics of a QS are system stability, the average number of requests in the system, and the average time a request spends in the system.

It should be emphasised that the stability condition in queueing systems is the requirement under which the system does not “collapse” over time, that is, the queue does not grow without bound. Therefore, the system is stable if service in the system is performed, on average, faster than requests arrive. If, conversely, requests arrive faster than they can be served, the queue will grow without bound, and the system will be unstable. Formally, this is expressed as follows. The utilisation coefficient is:

$$\rho = \frac{\lambda}{\mu_{system}},$$

where λ is the arrival intensity of requests;

$\mu_{system}$ is the total service capacity.

Accordingly, the stability condition is $\rho < 1$,

or:

$$\rho = \frac{\lambda}{\mu_{eff}} < 1,$$

or:

$$\lambda < \mu \cdot \frac{\beta}{\alpha+\beta}.$$

If $\rho > 1$ or ρ equals 1, the average queue length $L$ and the waiting time $W$ tend to infinity ($L \to \infty$, $W \to \infty$). As a result, no stationary regime exists, and the system is overloaded. Even if $\rho < 1$ but is close to 1, the queue will be very large and delays will be significant. This is illustrated by a simple example. If 10 requests per unit of time (minute, day) arrive in the system, while the system can serve 8 requests per unit of time, then $\rho = 10/8 = 1{,}25 > 1$; the system is unstable and the queue grows without bound. If the system serves 12 requests per unit of time, then $\rho = 10/12 = 0{,}83$, meaning that the system is stable. The stability condition is a balance of flows: the input flow must not exceed the output flow.

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For the *M/M/n* model: $\lambda < n\mu$. For the *M/M/n* model with unreliable channels: $\lambda < n \cdot \mu \cdot \beta/(\alpha + \beta)$.

The average number of requests in the system, including those being served and those in the queue, may be calculated using the formula for a system with several channels:

$$L = \frac{\rho}{1-\rho},$$

where ρ is the load on the system, that is, the ratio of the arrival intensity of requests to the effective service intensity.

If $\rho \to 1$, the queue length increases according to an exponential-type dependence: at $\rho = 0{,}4$, $L = 0{,}67$; at $\rho = 0{,}5$, $L = 1$; at $\rho = 0{,}8$, $L = 4$; at $\rho = 0{,}9$, $L = 9$; and at $\rho = 0{,}99$, $L = 99$. Thus, when $\rho \to 1$, the curve rises sharply (Figure 1).

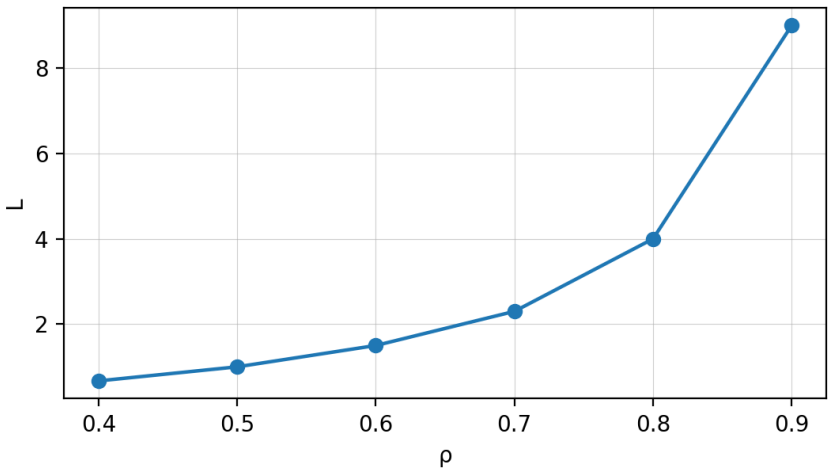



**Figure 1.** Dependence of queue length *L* on the value of *ρ*

The above dependence leads to an important practical conclusion: in real systems, the value of *ρ* should be *ρ = 0,6...0,8* rather than “almost 1”; otherwise, delays become unstable and the system behaves unpredictably, as shown in Figure 1.

The average time a request spends in the system, including waiting time and service time, is found through the reciprocal of the effective intensity:

$$W = \frac{1}{\mu_{eff} - \lambda},$$

where $\mu_{eff} = n \cdot \mu \cdot \beta/(\alpha + \beta)$.

**2. Multichannel QS with Stochastic Degrading Channels**

Multichannel QS with degrading channels are systems with several service channels in which channel performance may decrease. The concept of channel degradation consists in a reduction of service efficiency. Degradation may depend on operating time or on the number of requests: the more requests there are, the worse the channels operate. Degradation is characterised by a random change of state: “normal”, “deteriorated”, or “failure”.

Degradation may manifest itself in the following ways:

– an increase in the average service time of requests (a decrease in the service intensity *μ*);

– partial or complete channel failures;

– dependence of μ on operating time, the number of requests in the QS, and the state of the system.

The state of the system is described as *X(t) = (k, s)*, where *k* is the number of requests in the system and *s* is the state of the channels (degree of degradation). Transition intensities are as follows:

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arrival of requests $\lambda$; service depends on the state of the channels $\mu_s$.

The main characteristics are:

– probabilities of states $P_k$;

– average queue length $L_q$;

– average waiting time $W_q$;

– channel utilisation.

**Construction of the State Model**

Step 1. Definition of states.

For example: $k = 0, 1, 2, \ldots$ ; $s = 0$ – normal state; $s = 1$ – degraded state.

Then the states are: (0,0), (1,0), (2,0), … , (0,1), (1,1), …

Step 2. Set transition intensities:

– arrival – λ;

– service – $\mu_s$ ($\mu_1 < \mu_0$);

– degradation – $\alpha$;

– restoration – $\beta$.

Compilation of the Kolmogorov equations.

For the stationary regime:

$$\frac{dP_{k,s}}{dt} = 0.$$

A system of linear equations is obtained (an example, since the specific form depends on the model):

$$\lambda P_{k-1,s} + \mu_s P_{k+1,s} + \beta P_{k,1} = (\lambda+\mu_s+\alpha)\, P_{k,s}$$

The normalisation condition is: $\sum_{k,s} P_{k,s}=1$.

After determining the probabilities $P_{k,s}$, the characteristics are calculated: the average number of requests in the system, the average queue length, the average time in the system, the average waiting time, and channel utilisation.

The average number of requests in the system is:

$$L=\sum_{k,s} k \cdot P_{k,s},$$

The average queue length is:

$$L_q = \sum_{k>n} (k-n)\, P_{k,s},$$

The average time in the system is calculated using Little's formula:

$$W = L/\lambda,$$

and, accordingly, the average waiting time is:

$$Wq = L_q/\lambda;$$

channel utilisation is: $\rho = \lambda/(n \cdot \mu eff)$, where $\mu_{eff} = \sum_s \mu_s \cdot P$ (s).

The specific features of calculating QS with degrading channels lie in the fact that an analytical solution is often impossible, while the system of equations may be large or even infinite. Therefore, the state space is reduced according to the rule $k \leq K_{max}$.

Thus, in abbreviated form, the algorithm for calculating a QS with degrading channels is as follows:

1. Set λ, $\mu_o$, and the degradation parameters α and β.
2. Construct the states *(k, s)*.
3. Write the Kolmogorov equations.
4. Add normalisation.
5. Solve the system.
6. Calculate $L$, $W$, $L_q$, $W_q$, $\rho$.

**Examples**

Let us consider two illustrative examples of applying the apparatus of a multichannel QS:

– with unreliable channels;

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– with degrading channels.

**Example 1**

Assume that a certain QS contains 3 channels, the arrival intensity of requests into the system is $\lambda = 4$ per unit of time (for example, per day), the service intensity of requests is $\mu = 5$ per unit of time, the failure intensity is the same for all channels and equals $\alpha = 1$ per unit of time, and the restoration intensity equals $\beta = 2$ per unit of time.

In this case, the effective service intensity for one channel is:

$$\mu_{eff} = 5 \cdot 2 / (1 + 2) = 5 \cdot 2 / 3 \approx 3,33 \text{ requests per unit of time.}$$

The effective service intensity for all 3 channels is:

$$\mu_{eff} = 3 \cdot 3,33 = 10 \text{ requests per unit of time.}$$

The stability condition of the system is calculated as:

$$\rho = 4 / 10 = 0,4,$$

which means that the system is stable, since ρ is less than 1.

The expected number of requests in the system is:

$$L = [0,4 / (1 - 0,4)] \cdot 3 = [0,4 / 0,6] \cdot 3 = 2 \text{ requests.}$$

The average time a request spends in the system is:

$$W = 1 / (10 - 4) = 1 / 6 \approx 0,167 \text{ units of time.}$$

**Example 2**

Initial data.

We have an *M/M*/2 queueing system with degradation. The arrival intensity is $\lambda = 4$. The QS contains 2 channels:

– normal state – $\mu_0 = 3$ (each channel), hence $2\mu_0 = 6$;

– degraded state – $\mu_1 = 2$, hence $2\mu_1 = 4$;

– the probability of system degradation is $p = 0,3$.

The effective service intensity is calculated as:

$$\mu_{eff} = (1 - p) \cdot \mu_0 + p \cdot \mu_1,$$

therefore, for one channel:

$$\mu_{eff} = 0,7 \cdot 3 + 0,3 \cdot 2 = 2,1 + 0,6 = 2,7;$$

for 2 channels:

$$n \cdot \mu_{eff} = 2 \cdot 2,7 = 5,4.$$

Calculation of the utilisation coefficient:

$$P = \lambda / (n \cdot \mu_{eff}) = 4 / 5,4 \approx 0,741,$$

that is, the utilisation coefficient of the system is $\rho < 1$, which means that the system is stable.

Calculation of the idle probability $P_0$ for an *M/M/n* queueing system is carried out using the following formula:

$$P_0 = [\sum_{k=0}^{n-1} \frac{(\lambda/\mu)^k}{k!} + \frac{(\lambda/\mu)^n}{n!} \cdot \frac{1}{1-\rho}]^{-1},$$

where $\lambda/\mu_{eff} = 4 / 2,7 \approx 1,48$.

We calculate:

$$\sum_{k=0}^{1} = 1 + 1,48 = 2,48,$$

$$(1,48)2/2 = 2,19/2 = 1,095,$$

$$\frac{1}{1-\rho} = \frac{1}{1-0,741} = \frac{1}{0,259} \approx 3,86.$$

$$1,095 \cdot 3,86 \approx 4,23$$

$$P_0 = \frac{1}{2,48+4,23} = \frac{1}{6,71} \approx 0,149.$$

Calculation of the average queue length $L_q$:

$$Lq = \frac{(\lambda/\mu)^n \cdot \rho}{n! \cdot (1-\rho)^2} \cdot P_0,$$

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$$Lq = \frac{2{,}19 \cdot 0{,}741}{2(0{,}259)^2} \cdot 0{,}149 \approx 1{,}8.$$

Calculation of the average waiting time:

$$W_q = L_q/\lambda = 1{,}8/4 = 0{,}45.$$

Calculation of the average time in the system:

$$W = W_q + (1/\mu_{eff}) = 0{,}45+1/2{,}7 \approx 0{,}82.$$

Calculation of the average number of requests in the system:

$$L = \lambda \cdot W = 4 \cdot 0{,}82 = 3{,}28.$$

If the degree of degradation increases, all characteristics of the system increase accordingly. For illustration, let us increase the probability from 0,3 to 0,6. The results are presented in Table 1.

**Table 1.** Changes in System Characteristics Due to Degradation

| **Indicator** | ***p* = 0,3** | ***p* = 0,6** |
|---|---|---|
| Utilisation $\rho$ | 0,741 | 0,833 |
| Queue length $L_q$ | 1,8 | 3,76 |
| Waiting time $W_q$ | 0,45 | 0,94 |
| Time in the system $W$ | 0,82 | 1,36 |
| Number of requests in the system $L$ | 3,28 | 5,44 |

Thus, the conclusion may be drawn that an increase in the degree of degradation brings the system closer to a critical state ($\rho \to 1$), increases the queue of requests almost twofold, and also almost doubles the waiting time.

From the standpoint of forming the structure and composition of the AMSE repair system, these results show that the number of nominal repair channels alone cannot be considered a sufficient criterion for determining repair capabilities. The actual capacity of a repair unit depends not only on the number of repair teams, workshops or workplaces, but also on the probability of their failure, the intensity of restoration, and the degree of degradation of service performance under combat conditions. Therefore, the proposed approach makes it possible to substantiate not only the required number of repair channels, but also the necessary reserve of repair capacity to prevent the system from approaching a critical utilisation level.

## Conclusion

The article proposes an improved methodological approach to forming the structure and composition of the AMSE repair system. The approach is based on assumptions regarding the unreliability of channels in a QS and the presence of degrading channels. This approach makes it possible to form a rational structure of the repair system both as a whole and by elements, and to calculate its characteristics. The examples presented demonstrate the possibility of practical application of the proposed methodological approach for forming a rational structure of the AMSE repair system and obtaining rational values of its parameters.

Prospects for further research include determining the possibility of using queueing theory in cases where the service duration of requests at all nodes is a random variable distributed not according to the exponential law, but according to other laws.

## Recommendations

The proposed methodological approach should be used when substantiating the required structure and composition of AMSE repair units and subunits under modern combat conditions.

When planning repair capabilities, it is advisable to take into account not only the nominal number of repair channels, but also their reliability, restoration intensity and possible degradation of service performance.

The utilisation coefficient ρ should be used as one of the key control indicators for assessing the stability of repair units. In practical planning, it is advisable to avoid values of ρ close to 1 and to

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maintain a reserve of repair capacity.

Further development of the approach should be aimed at modelling repair systems in which service times are distributed according to laws other than the exponential distribution.

**Conflict of Interest**

The authors declare that they have no competing interests related to the subject of the article.

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## Удосконалений методичний підхід до формування структури та складу системи ремонту озброєння, військової та спеціальної техніки у Збройних Силах України

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**Анотація.** Статтю присвячено удосконаленню методичного підходу до формування структури та складу системи ремонту озброєння, військової та спеціальної техніки на основі використання теорії систем масового обслуговування з урахуванням особливостей сучасних бойових дій. Досвід відсічі збройної агресії російської федерації переконливо свідчить про те, що виробничі спроможності системи ремонту є недостатніми для своєчасного виконання завдань щодо ремонту пошкоджених зразків озброєння, військової та спеціальної техніки. Аналіз функціонування системи ремонту озброєння, військової та спеціальної техніки в умовах бойових дій показує, що структура та склад ремонтних органів не відповідають сучасним вимогам. Тому система ремонту озброєння, військової та спеціальної техніки у Збройних Силах України потребує більш детального розгляду. Для цього модель системи ремонту може бути представлена у вигляді мережі масового обслуговування. У цій мережі окремі ланки доцільно представляти як багатоканальні системи масового обслуговування з ненадійними або деградуючими каналами. Метою статті є удосконалення методичного підходу до формування структури та складу системи ремонту озброєння, військової та спеціальної техніки на основі мережі масового обслуговування з урахуванням особливостей сучасних бойових дій. Методологічну основу дослідження становить комплексне використання теорії масового обслуговування, теорії ймовірностей, системного моделювання, порівняльного аналізу та аналітичного узагальнення для представлення ремонтних підрозділів як елементів мережі масового обслуговування з ненадійними та стохастично деградуючими каналами обслуговування. Наукова новизна полягає у представленні ремонтних підрозділів як багатоканальних систем масового обслуговування, у яких частина каналів є ненадійними або деградуючими, що дає змогу більш точно та об'єктивно визначати структуру та склад ремонтних підрозділів. Удосконалений методичний підхід дозволяє завчасно та на обґрунтованій основі визначати параметри ремонтних підрозділів під час формування структури та складу системи ремонту озброєння, військової та спеціальної техніки.

**Ключові слова:** система ремонту; озброєння, військова та спеціальна техніка; озброєння, військова та спеціальна техніка; система масового обслуговування; мережа масового обслуговування; ненадійні канали; деградуючі канали; ремонтні підрозділи; інтенсивність бойових дій.