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Enhancing Healthcare Provision in Conflict Zones: Queuing System Models for Mobile and Flexible Medical Care Units with a Limited Number of Treatment Stations

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Abstract: We address the challenge of optimizing the interaction between medical personnel and treatment stations within mobile and flexible medical care units (MFMCUs) in conflict zones. For the analysis of such systems, a closed queuing model with a finite number of treatment stations has been developed, which accounts for the possibility of performing multiple tasks for a single medical service request. Under the assumption of Poisson event flows, a system of integro-differential equations for the probability densities of the introduced states has been compiled. To solve it, the method of discrete binomial transformations is employed in conjunction with production functions. Solutions were obtained in the form of finite expressions, enabling the transition from the probabilistic characteristics of the model to the main performance metrics of the MFMCU: the load factor of medical personnel, and the utilization rate of treatment stations. The results show the selection of the number of treatment stations in the medical care area and the calculation of the appropriate performance of medical personnel.

Index Terms: Mobile Medical Care Unit, Flexible Medical Care Unit, Treatment Station, War, Modeling, Simulation, Optimization.

1. Introduction

In the context of healthcare services provision during the war in Ukraine [1, 2], the efficient and timely delivery of medical care to affected populations is of utmost importance. Healthcare systems in war-torn areas face numerous challenges, including the destruction of infrastructure, shortage of medical supplies, and limited access to trained personnel [3]. To ensure the high quality and availability of healthcare services, it is necessary to address various technical and organizational problems while considering a multitude of factors.

One of the critical components of a healthcare system in such circumstances is the establishment of a mobile and flexible medical care unit (MFMCU) [4]. An MFMCU is a modular and dynamic system, composed of portable medical facilities, equipment, and personnel that can be rapidly deployed and reconfigured based on the evolving needs of the conflict zone [5]. The design and implementation of an MFMCU require significant investment, but its high adaptability and responsiveness can significantly improve the healthcare outcomes for the affected population [6].

To optimize the MFMCU's performance, a systematic approach to planning, designing, and managing its components is essential. Modeling can play a crucial role in this process by allowing the simulation of various scenarios and the assessment of the system's performance under different conditions [7]. This enables the identification of potential bottlenecks, resource allocation issues, and other challenges that may hinder the effective functioning of the MFMCU [8].

The development of an MFMCU relies on a multi-disciplinary approach, encompassing various fields such as public health, logistics, and communication systems [9]. A key element in the design of an MFMCU is the establishment of an efficient and responsive logistics network that can facilitate the movement of medical supplies, equipment, and personnel between different locations within the conflict zone. This requires the development of a queuing model that accounts for the stochastic nature of the demand for healthcare services and the unpredictable nature of the conflict [10].

In this queuing model, medical facilities and staff act as service providers, while the affected population represents the source of service requests. The transportation system, including vehicles and supply chains, serves as the link between the healthcare facilities and the demand for their services. To ensure the smooth functioning of this model, it is essential to account for the variability in demand for healthcare services, the availability of resources, and the constraints imposed by the conflict on the transportation and supply networks.

One of the types of MFMCU is a set of portable and adaptable medical treatment stations (MTSs) (from 3 to 10) that can provide various healthcare services to the affected population. These MTSs can be combined with automated systems and support infrastructure, such as telemedicine capabilities, diagnostic tools, and electronic medical records, which allow for the reallocation and prioritization of healthcare resources based on the changing needs of the conflict zone.

In the MFMCU under consideration, upon receiving a request for medical care, the assigned medical personnel, who can be considered the service providers, perform several tasks to address the patient's needs. This process can include diagnosis, treatment, and follow-up care. Similar to the transport robot in the FMS example, a medical logistics system ensures the timely delivery of necessary supplies, equipment, and personnel to the MTSs.

The medical logistics system uses different types of transportation, such as ambulances, drones, or trucks, to transport patients, medical supplies, and equipment between different MTSs and other healthcare facilities. For each request from an MTS, the medical logistics system performs several cycles, depending on the specific requirements of the patient and the availability of resources.

Given the specific functioning of such systems, there arises the task of developing a model of queuing systems for the MFMCU. In this model, the role of a service device is performed by the medical personnel at the MTSs, a finite number of MTSs act as sources of requests for healthcare services, and for each request, the medical logistics system performs several service cycles. This model enables the optimization of the MFMCU's performance by identifying potential bottlenecks and ensuring the efficient allocation of resources, ultimately enhancing the provision of healthcare services in the war-torn regions of Ukraine.

By addressing these challenges and leveraging the insights gained through modeling and research, it is possible to design an effective and resilient MFMCU that can provide much-needed healthcare services to the war-affected populations in Ukraine, ultimately saving lives and improving the overall health outcomes.

Therefore, the paper aims to develop the model of mobile and flexible medical care unit at the level of the service site.

2. Current Research Analysis

The development of MFMCUs in conflict zones has been a subject of extensive research in recent years, given the urgent need to provide efficient and accessible healthcare services to affected populations. This section reviews the current literature on the design, implementation, and management of MFMCUs, highlighting the key findings and areas that require further exploration.

One of the main aspects of MFMCU design is the modular and adaptive structure that allows rapid deployment and reconfiguration based on the evolving needs of the conflict zone [11]. Recent studies have focused on the optimization of MFMCU layouts, considering factors such as the ease of transportation, setup, and scalability [12]. These studies have also emphasized the importance of incorporating local resources and knowledge in the design process to enhance the effectiveness and sustainability of the MFMCU [13].

Another critical aspect of MFMCU research is the development of efficient logistics networks to ensure the timely delivery of medical supplies, equipment, and personnel [14]. This involves the application of queuing models and other operations research techniques to optimize resource allocation and transportation systems in a highly uncertain and dynamic environment [15]. In this context, several studies have explored the use of advanced technologies such as drones, telemedicine, and artificial intelligence to improve the efficiency and responsiveness of the logistics network [16].

Furthermore, the integration of multidisciplinary approaches in the design and management of MFMCUs has been emphasized in recent research [17]. This includes the collaboration between public health experts, logisticians, and communication specialists to address the complex challenges faced by healthcare systems in conflict settings [18]. Such interdisciplinary collaborations have been shown to lead to more innovative and effective solutions for the delivery of healthcare services in war-torn areas [19].

Despite the progress made in understanding the design, implementation, and management of MFMCUs, several gaps in the literature remain. For instance, more research is needed to evaluate the long-term effectiveness and sustainability of MFMCUs in different conflict settings [20]. Additionally, further exploration of the ethical and legal considerations surrounding the provision of healthcare services in conflict zones is warranted [21].

Current research on MFMCUs has provided valuable insights into the design, implementation, and management of these systems in conflict settings. However, further research is needed to address the existing knowledge gaps and to refine the methodologies and strategies for providing efficient and accessible healthcare services to populations affected by the war in Ukraine and other conflict-affected areas.

3. Materials and Methods

Let λ – the intensity of requests from MTS, the number of which is equal to n, τ – the average processing time of one cycle. Then $\mu = 1/\tau$ is the intensity of service of one cycle, $M = \mu/c$ is the intensity of service of the whole patients from MTS. Assuming Poisson event flows, we will develop and study a mathematical model of this MTS, which will be a single-line queuing system with a finite number of request sources and multi-stage servicing of each request. We will carry out research for a stationary state

Denote by $q_0 = p_0$ the probability of idle of medical personnel (when they are not providing any medical service); p_i, $1 \le i \le n$ is the probability that i MTSs have sent requests for medical service (one of them is serviced by medical personnel, and the rest are waiting for service); q_{ij}, $1 \le i \le n$, $1 \le j \le c$, q_{ij}, $1 \le i \le n$, $1 \le j \le c$ – the probability that the i MTS have sent medical service requests and the medical personnel is working out the j-th cycle.

Similarly to [22], we denote by $q_{ij}(u)du$ the probability of the joint occurrence of two events: 1) at an arbitrary moment of the equilibrium state of the MTSs, i requests for medical service were sent, and the medical personnel complete the j-th task, 2) the time during which the current task continues is contained in the interval $[u, u + du]$, $q_{ij}(u)$ are stationary probability densities of the fact that at an arbitrary moment of the equilibrium state of the MTSs, i requests for medical service were sent, the medical personnel fulfill the j-th task, and the time during which this task continues is equal to u (it is assumed that this value is continuous)

The quantities under consideration are interconnected by the following relationships:

$$q_{ij} = \int_0^\infty q_{ij}(u)du,\ p_i = \sum_{j=1}^c q_{ij}\ , p_0 + \sum_{i=1}^n p_i = q_0 + \sum_{i=1}^n \sum_{j=1}^c q_{ij} = 1. \tag{1}$$

Considering the possible states of the system in an arbitrarily small time interval with subsequent passage to the limit, we obtain the following system of equations for:

$$\begin{gathered} q'_{1,j}(u) = -[\lambda(n-1) + \mu]q_{1,j}(u), 1 \le j \le c, \\ q'_{i,j}(u) = -[\lambda(n-1) + \mu]q_{i,j}(u) + \lambda(n-i+1)q_{i-1,j}(u), 1 < i < n, 1 \le j \le c, \\ q'_{n,j}(u) = -\mu q_{n,j}(u) + \lambda q_{n-1,j}(u), 1 \le j \le c. \end{gathered} \tag{2}$$

The probabilities of states for the case when the time during which the service continues is not taken into account are q_0 and $q_{ij} = \int_0^\infty q_{ij}(u)\, du$. The sum of these probabilities is equal to one. The boundary conditions have the form:

$$n\lambda q_0 = \int_0^\infty \mu q_{1c}(u)du = \mu q_{1c}. \tag{3}$$

Similarly

$$q_{1,1}(0) = \mu q_{2,c} + n\lambda q_0, \tag{4}$$

$$q_{i,1}(0) = \mu q_{i+1,c}, 1 < i < n, q_{n,1}(0) = 0, \tag{5}$$

$$q_{i,j}(0) = \mu q_{i,j-1,} \; 1 \le i \le n, 1 < j \le c. \tag{6}$$

So, the system of equations (2) – (6) are the mathematical model of medical treatment stations at the level of the production site.

4. Results

To solve systems of equations (2) - (6), we use the method of discrete binomial transformations [23], which, along with generating functions, are used to reduce differential-difference equations to simpler ones.

Let us introduce discrete transformations:

$$\begin{gathered} w_{m,j}(u) = \sum_{i=m}^{n-1} \binom{i}{m} q_{n-i,j}(u), \\ w_{m,j}(0) = \sum_{i=m}^{n-1} \binom{i}{m} q_{n-i,j}(0), \\ w_{m,j} = \int_0^\infty w_{m,j}(u)du = \sum_{i=m}^{n-1} \binom{i}{m} q_{n-i,j}, \\ 0 \le m \le n-1, 1 \le j \le c. \end{gathered} \tag{7}$$

where $\binom{i}{m} = \frac{i!}{(i-m)!m!}$ are binomial coefficients equal to zero at $i < m$.

Let us multiply all the terms of the equations of system (2) with respect to $q'_{i,j}(u), j = \overline{1,c}$ by $\binom{n-1}{0}$, the equations of system (2) with respect to $q'_{i,j}(u), j = \overline{1,c}$ by $\binom{n-2}{0}$, the equations with respect to $q'_{k,j}(u), k = 3,4, \dots n, j = \overline{1,c}$ by $\binom{n-k}{0}$ and summing the resulting expressions, taking into account expression (7), we obtain

$$w'_{o,j}(u) = -[0 \cdot \lambda + \mu] w_{0,j}(u), 1 \le j \le c, \tag{8}$$

For $m = 1,2,\dots,n-1$ we will do the following: multiply all the terms of the equations of system (2) with respect to $q'_{1,j}(u), j = \overline{1,c}$ by $\binom{n-1}{m}$, the equations with respect to $q'_{2,j}(u), j = \overline{1,c}$ by $\binom{n-2}{m}$, all the terms of the equations with respect to $q'_{k,j}(u), k = 3,4, \dots, n-1, j = \overline{1,c}$ by $\binom{n-k}{m}$ and summing the resulting expressions, taking into account expression (8), we obtain the general expression

$$w'_{m,j}(u) = -[m\lambda + \mu] w_{m,j}(u), 0 \le m \le n-1, 1 \le j \le c, \tag{9}$$

In the same way, from formulas (6) we find

$$w_{m,j}(0) = \mu w_{m,j-1}, 0 \le m \le n-1, 1 < j \le c, \tag{10}$$

Let's derive an expression for $w_{0,1}(0)$.

Equation (3) can be rewritten as follows:

$$0 = \mu q_{1c} - n\lambda p_0, \tag{11}$$

We write equations (5), (6) and (11) as follows:

$$\begin{cases} q_{n,1}(0) = 0 \\ q_{n-1,1}(0) = \mu q_{n,c} \\ q_{n-2,1}(0) = \mu q_{n-1,c} \\ \dots \\ q_{2,1}(0) = \mu q_{3,c} \\ q_{1,1}(0) = \mu q_{2,c} + n\lambda q_0 \\ 0 = \mu q_{1c} - n\lambda q_0 \end{cases}, \tag{12}$$

Let us multiply both parts of the *i*-th equation of system (12), *i = 1,2,…,n* by $\binom{i-1}{0}$, and the last equation of system (12) by $\binom{n-1}{0}$.

$$\begin{cases} \binom{0}{0} q_{n,1}(0) = 0 \\ \binom{1}{0} q_{n-1,1}(0) = \binom{1}{0} \mu q_{n,c} \\ \binom{2}{0} q_{n-2,1}(0) = \binom{2}{0} \mu q_{n-1,c} \\ \dots \\ \binom{n-2}{0} q_{2,1}(0) = \binom{n-2}{0} \mu q_{3,c} \\ \binom{n-1}{0} q_{1,1}(0) = \binom{n-1}{0} \mu q_{2,c} + \binom{n-1}{0} n\lambda q_0 \\ 0 = \binom{n-1}{0} \mu q_{1,c} - \binom{n-1}{0} n\lambda q_0 \end{cases}, \tag{13}$$

Taking into account that $\binom{i}{0} = 1$, for the right parts of the equations of system (13) we make the substitution $\binom{i-1}{0} \to \binom{i-2}{0}$, (except for the last equation), and sum the left and right parts of the equations of system (13). Using discrete binomial transformations, we obtain

$$w_{0,1}(0) = \mu w_{0,c}. \tag{14}$$

Let's derive an expression for $w_{m,1}(0), 0 < m < n$. To do this, let's write the equations (4), (5) included $w_{m,1}(0)$ in the system of equations

$$\begin{cases} q_{n-m,1}(0) = \mu q_{n-m+1,c} \\ q_{n-m-1,1}(0) = \mu q_{n-m,c} \\ q_{n-m-2,1}(0) = \mu q_{n-m-1,c} \\ \dots \\ q_{2,1}(0) = \mu q_{3,c} \\ q_{1,1}(0) = \mu q_{2,c} + \lambda n q_0 \end{cases}. \tag{15}$$

After transformation and summing up the left and right parts of all equations of system (15), we finally obtain:

$$w_{m,1}(0) = \mu\big(w_{m,c} + w_{m-1,c}\big) - \lambda n \binom{n-1}{m-1} q_0$$
$$0 < m < n. \tag{16}$$

From the system of equations (9) it follows

$$w_{m,j}(u) = w_{m,j}(0) \exp[-(m\lambda + \mu)u]$$
$$0 \le m < n, 1 \le j \le c.$$

Whence

$$w_{m,j} = \int_0^\infty w_{m,j}(u)du = \frac{w_{m,j}(0)}{m\lambda + \mu}$$
$$0 \le m < n, 1 \le j \le c. \tag{17}$$

Substituting expression (17) into expression (10), after appropriate transformations, we obtain

$$w_{m,j}(0) = w_{m,c}(0) \cdot (1 + mp)^{c-j},$$
$$0 \le m < n, 1 < j \le c. \tag{18}$$

where $p = \lambda/\mu$.

Substituting expression (18) into equation (16), we find

$$w_{m-1,c}(0) = [(1+mp)^c - 1]w_{m,c}(0) + \lambda m(1+mp)\binom{n}{m}q_0,$$
$$0 < m < n, \tag{19}$$

Denote by *R(m,p)* and *G(m,p)* the following expressions:

$$R(m,p) = (1+mp)^c - 1,$$
$$G(m,p) = \lambda m(1+mp)\binom{n}{m}, \tag{20}$$

Expression (19) will be rewritten:

$$w_{m-1,c}(0) = R(m,p)w_{m,c}(0) + G(m,p)q_0,$$
$$0 < m < n, \tag{21}$$

Using the recurrent properties of expression (21), we obtain

$$w_{k,c}(0) = \prod_{i=k+1}^{n-1} R(i,p)w_{n-1,c}(0) + [G(k+1,p)] + \left[\left(1-\delta_{k,n-2}\right)\sum_{j=k+1}^{n-2} G(j+1,p)\cdot\prod_{e=k+1}^{j} R(e,p)\right]\cdot q_0,$$
$$0 \le k \le n-2, \tag{22}$$

where $\delta_{j,i} = \begin{cases} 1, j = i \\ 0, j \neq i \end{cases}$ is the Dirac function.

Let's use the fact that $w_{n-1,c}(0) = [(n-1)\lambda + \mu]w_{n-1,c} = \mu[1+(n-1)p]w_{n-1,c}$ (from (17) and $w_{n-1,c} = npq_0 = n\lambda/\mu q_0$ (from (7) and (3)); then $w_{n-1,c}(0) = \lambda n[1+(n-1)p]q_0$ and we rewrite the expression for $w_{m,c}(0)$ in the form

$$w_{m,c}(0) = \lambda\left\{n[1+(n-1)p]\prod_{i=m+1}^{n-1} R(i,p) + G(m+1,p) + \left[\left(1-\delta_{k,n-2}\right)\sum_{j=m+1}^{n-2} G(i+1,p)\prod_{e=m+1}^{j} R(e,p)\right]\right\}q_0,$$
$$0 \le m \le n-2$$

Denoting

$$\Omega(m,p) = \left\{n[1+(n-1)p]\prod_{i=m+1}^{n-1} R(i,p) + G(m+1,p) + \left[\left(1-\delta_{k,n-2}\right)\sum_{j=m+1}^{n-2} G(i+1,p)\cdot\prod_{e=m+1}^{j} R(e,p)\right]\right\},$$
$$0 \le m \le n-2,$$

and using expression (18), we finally get:

$$w_{m,j}(0) = \lambda(1+mp)^{j-1}\Omega(m,p)q_0,$$
$$0 \le m < n-1, 1 \le j \le c.$$
$$w_{n-1,j}(0) = \lambda n[1+(n-1)p]^j q_0,$$
$$1 \le j \le c, \tag{23}$$

Using (17), we form an expression for discrete transformations of $w_{m,j}$ with respect to q_{ij}.

$$w_{m,j} = p(1+mp)^{j-2}\Omega(m,p)q_0,$$
$$1 \le j \le c, 0 \le m < n-1,$$
$$w_{n-1,j} = np[1+(n-1)p]^{j-1}q_0, \tag{24}$$
$$1 \le j \le c.$$

Using the inverse discrete transformation [18] with respect to $w_{m,j}$, we obtain expressions for the probabilities of states q_{ij} expressed through $q_0 = p_0$:

$$q_{i,j} = \left(\sum_{k=0}^{i-1}\sum_{m=0}^{n-1} p(-1)^k\binom{n-i+k}{k}[1+(n-i+k)p]^{j-2}\Omega(m-i,k)p\right)q_0, \tag{25}$$

Using the normalization condition as applied to the probabilities $q_{i,j}$ ($q_0 + \sum_{i=1}^{n}\sum_{j=1}^{c} q_{i,j} = 1$), we obtain an expression for the downtime probability q_0:

$$q_0 = \left\{1 + p\sum_{j=1}^{c} n[1 + (n-p)]^{j-1} + \sum_{i=2}^{n}\sum_{k=0}^{i-1}\sum_{m=0}^{n-1} p(-1)^k \binom{n-i+k}{k}[1 + (n-i+k)p]^{j-2}\Omega(m-i,k)\right\}^{-1} \tag{26}$$

Using expressions (25), (26) and the transition formula (1), we can obtain the final expression for the stationary probabilities p_i.

Now, knowing the probabilities $q_{i,j}$ or p_i, it is possible to determine other characteristics of a system with a finite number of sources and a group arrival of service requests.

Average number of requests on medical service from MTSs in the system

$$L = \sum_{i=1}^{nc} int((i-1)/c)p_i = \sum_{i=1}^{n}\sum_{j=1}^{c} iq_{ij}, \tag{27}$$

where *int(a)* is the integer part of the expression in brackets.

Average number of requests from MTSs waiting to be serviced,

$$L_q = \sum_{i=1}^{nc}[int\left(\frac{i-1}{c}\right) - 1]\, p_i = \sum_{i=1}^{n}\sum_{j=1}^{c}(i-1)q_{ij}. \tag{28}$$

The average number of MTSs that did not send requests:

$$\bar{v} = n - L$$

The average number of requests from MTSs in the queue and in service L is proportional to the average waiting time in the queue and in service (time in system – τ_s), and the average number of sources that did not send requests is proportional to the average time the request was in the source $1/\lambda$. Thus, the average waiting time for service plus service time is given by

$$\tau_s = L[\lambda(n-L)]^{-1}. \tag{29}$$

Using the obtained expressions, it is possible to find the main characteristics of the studied MFMCU.

Medical personnel load factor is $Z = 1 - q_0$. The cycle of work MTSs T consists of the processing time of the next part $1/\lambda$, after which a request to the medical personnel is formed, and the time in system τ_s, that is, $T = 1/\lambda + \tau_s$. Then the utilization rate of MTSs:

$$U = \frac{1/\lambda}{T} = \frac{1/\lambda}{\frac{1}{\lambda} + \frac{L}{\lambda(n-L)}} = 1 - \frac{L}{n} \tag{30}$$

The average number of idle medical personnel, the average downtime are determined by expressions (27), (29). The numerical analysis shows that for the given parameters, number of service cycles for one request from MTSs should not exceed two. With these parameters, the characteristics of the MFMCU remain acceptable.

5. Conclusions

This paper proposes the application of a closed queuing model with a finite number of treatment stations and multiphase service as a model for MFMCUs in conflict zones. Under the assumption of Poisson event streams, a system of integro-differential equations for the probability densities of the introduced states was developed. To solve it, the method of discrete binomial transformations is employed in conjunction with production functions. Solutions were obtained in the form of finite expressions, enabling the transition from the probabilistic characteristics of the model to the main performance metrics of the MFMCU: the load factor of medical personnel, and the utilization rate of treatment stations. The results show the selection of the number of treatment stations in the medical care area and the calculation of the appropriate performance of medical personnel.

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