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MATHEMATICAL MODEL OF DECISION MAKING DURING SEARCH AND RESCUE OPERATIONS AT SEA

Andrii Liamzin, Serhii Hodovaniuk, Iryna Borets, Viktoriia Klymenko. «Mathematical Model of Decision Making during Search and Rescue Operations at Sea». *The article considers the issue of increasing the efficiency of search and rescue operations management at sea by applying the provisions of the queuing theory. A mathematical model of decision support in the system of coordination of rescue units is proposed, which takes into account the stochastic nature of the receipt of applications and the limited bandwidth of service channels. Examples of calculations of the system functioning efficiency indicators are given, which confirm the feasibility of using intelligent decision support technologies (IQ technologies) to increase the* *efficiency of the response of search and rescue services. The practical significance of the use of mathematical modeling for reducing the time of information processing, making management decisions and transmitting commands to executors in difficult sea conditions is substantiated.*

Keywords: maritime transport, search and rescue operations, queuing theory, efficiency, decision-making, IQ technologies

Андрій Лямзін, Сергій Годованюк, Ірина Борець, Вікторія Клименко. «Математична модель прийняття рішень під час пошуково-рятувальних операцій на морі». *У статті розглянуто питання підвищення ефективності управління пошуково-рятувальними операціями (ПРМ) на морі шляхом застосування положень теорії масового обслуговування. Запропоновано математичну модель підтримки прийняття рішень у системі координації дій рятувальних підрозділів, яка враховує стохастичний характер надходження заявок і обмежену пропускну спроможність каналів обслуговування. Наведено приклади розрахунків показників ефективності функціонування системи, що підтверджують доцільність використання інтелектуальних технологій підтримки прийняття рішень (IQ-технологій) для підвищення оперативності реагування служб ПРМ. Обґрунтовано практичну значущість застосування математичного моделювання для скорочення часу оброблення інформації, ухвалення управлінських рішень і передачі команд виконавцям у складних морських умовах.*

Ключові слова: морський транспорт, пошуково-рятувальні операції, теорія масового обслуговування, ефективність, прийняття рішень, IQ-технології

Introduction. Over the past decades, the issues of ensuring the safety and efficiency of maritime transport have become increasingly relevant due to the intensification of global cargo flows, the expansion of transport and logistics corridors and the increasing complexity of international transport networks. The maritime sector remains one of the most dynamic elements of the global economy, accounting for more than 80% of international trade. At the same time, with the development of maritime transport, the number of emergencies at sea is increasing, requiring timely and clearly coordinated search and rescue activities.

The efficiency of maritime search and rescue operations is determined not only by the technical readiness of forces and means, but primarily by the quality of management decision-making and coordination of actions within the system. In practice, delays in processing distress signals, forming response priorities and distributing rescue resources often lead to critical time losses, which directly affects the results of rescue missions [1, 2]. That is why the optimization of management processes in the maritime search and rescue system is an important direction for increasing the efficiency of maritime logistics and ensuring shipping safety.

In modern scientific discourse, search and rescue operations management is considered as a component of logistics systems in which information, material and human flows are coordinated within a single management loop. This approach corresponds to the principles of adaptive logistics, which considers transport and emergency and rescue networks as dynamic systems with limited capacity and stochastic nature of functioning [3, 4]. From this perspective, the process of receiving and processing rescue requests can be described using the theory of queuing, which allows us to quantitatively assess the efficiency of the system and identify bottlenecks in the use of resources.

Relevance of research is due to the need to reduce the time for organizing and conducting rescue operations, which directly depends on the efficiency of collecting, processing and analyzing information, the speed of decision-making and transmitting commands to executors. The use of mathematical tools in this context creates a methodological basis for increasing the speed of management decisions, determining the optimal number of service channels and predicting the behavior of the system at different load levels [5–7].

In parallel, there is a steady trend in the maritime industry towards digitalization and the introduction of intelligent management technologies that provide real-time decision support based on data analytics and predictive algorithms [8, 9]. The integration of IQ technologies into the search and rescue operations management system contributes to increasing the adaptability of management processes, minimizing response delays and strengthening the resilience of maritime transport systems to crisis situations.

Therefore, the scientific problem addressed in the article is to develop and substantiate a mathematical model of decision-making in the maritime search and rescue system, built on the principles of the queuing theory and adaptive logistics. The proposed approach combines theoretical principles and practical mechanisms for managing dynamic information flows and can be used to increase the efficiency of maritime coordination and rescue centers within the integrated system of maritime transport and shipping safety.

Literature review. The formation of the maritime transport safety management system as an integrated interdisciplinary field is closely related to the development of logistics, management theory and operations research. Over time, maritime logistics has evolved from a narrowly functional understanding focused only on transportation and shipping planning to a strategic, systemic subject that encompasses efficiency, safety and environmental responsibility. This transformation is due to the growing complexity of global transport and logistics systems, the digitalization of operational processes and the need for effective management of emergencies at sea [1, 2].

The theoretical basis for modeling emergency situations and rescue processes at sea is the queuing theory, which has been actively used in transport research since the middle of the 20th century. The classic works of A. Erlang, D. Kendall and J. Little created a mathematical apparatus for analyzing random flows and service processes [3]. In the maritime industry, these principles were adapted for modeling the movement of sea vessels, port processes, and later for organizing search and rescue operations [4, 5].

Early research in the field of search and rescue management was mainly organizational, aimed at standardizing procedures and creating an international regulatory framework, in particular the International Aeronautical and Maritime Search and Rescue Manual (IAMSAR Manual), developed by ICAO and IMO [6]. These documents defined the structure of coordination centers, the procedure for information exchange, the division of responsibilities and the decision-making hierarchy. However, subsequent scientific research focused on the stochastic nature of distress signal flows and the need to use adaptive mathematical models to improve the efficiency of the management system [7].

At the end of the 20th and beginning of the 21st centuries, a number of Ukrainian scientists (Kondratyuk, 2020; Godovanyuk, 2020; Simonov, 2021) proposed applying logistics principles to the management of search and rescue processes at sea. They considered the maritime rescue system as a component of a transport and logistics network, within which the coordination of information and human flows determines the overall efficiency of the system [8–10]. In this context, the queuing model is used to describe the flow of applications, determine the probability of service, queue length, and average response time.

Modern research proves that modeling search and rescue operations requires a combination of deterministic and probabilistic approaches. Thus, according to the conclusions of Bakharev and Khokhlov (2020), the random nature of the occurrence of emergency events at sea allows the use of Poisson distributions and the exponential law to model the flow of applications and the duration of their service [11]. This makes it possible to determine critical points of system overload and its behavior under extreme conditions, for example, during storms or mass rescue operations.

At the same time, the development of intelligent maritime logistics has led to the introduction of digital and analytical technologies into the process of managing rescue operations. The use of simulation modeling, machine learning, and real-time decision support systems allows predicting vessel movement routes, detecting anomalies, and automating the coordination of rescue units [12, 13]. Studies by Pagonis and Balbo (2022), Shiryaev and Bogdanov (2021) confirm that the combination of mathematical modeling and artificial intelligence-based analytics increases the efficiency of marine emergency management [14, 15].

From the perspective of logistics theory, search and rescue management corresponds to the concept of adaptive logistics, according to which the system should respond flexibly to changes in the external and internal environment. As Trushkina and Dzvigol (2021) point out, modern logistics systems are based on the principles of flexibility, digital integration and resilience, which are the main factors of the efficiency of complex transport networks [16]. Accordingly, the integration of search and rescue systems into the broader digital ecosystem of maritime logistics reflects the global trend towards Logistics 4.0, which is characterized by automation, interconnectedness and predictive analytics [17, 18].

In addition, the concept of sustainable and resilient logistics has become widespread, within which the management of rescue processes should ensure a balance between the speed of response, the rational use of resources and the minimization of environmental impact [19, 20]. International organizations, in particular IMO and UNCTAD, emphasize that digital transformation, the implementation of intelligent systems, and taking into account the human factor are key conditions for creating resilient maritime infrastructures capable of effectively responding to emergencies [21, 22].

Thus, the literature review shows that the maritime search and rescue management system is gradually moving from static procedural models to adaptive, data-driven systems that integrate logistics principles, mathematical modeling, and intelligent technologies. This evolution is shaping a new interdisciplinary paradigm, within which maritime transport safety management is viewed as a field that combines logistics, mathematics, computer science, and control theory to achieve optimal levels of responsiveness, coordination, and resilience of maritime transport systems.

Purpose of research is to improve the efficiency of search and rescue operations management at sea by creating a mathematical model of decision-making based on the principles of the queuing theory. This approach allows to quantitatively assess the dynamics of information flows, determine the load on the control system and justify ways to reduce response time in the process of rescue operations.

To achieve the purpose, the following **objectives** were solved in the research:

– modern approaches to managing search and rescue operations at sea were analyzed;

– the possibilities of applying the queuing theory to model the processes of receiving and processing requests were considered;

– the diagram of managing search and rescue operations' logistical process was developed;

– examples of calculations of the main indicators of the system's efficiency were performed;

– conclusions regarding to the need of implementing the intelligent decision-making support technologies (IQ technologies) in the field of maritime rescue were formulated.

Research methodology is based on the use of theoretical-analytical and mathematical approaches. The main tool is the apparatus of the theory of queuing, which allows us to model the process of receiving applications, assess the system load and determine the probability of service failure. To describe practical situations, elements of simulation modeling and comparative analysis were used, which made it possible to assess the efficiency of the search and rescue service under different load conditions.

The research is analytical in nature and is based on the generalization of scientific publications, official documents of the International Maritime Organization (IMO) and the results of our own calculations. The conclusions obtained can be used to improve the organizational structure of maritime search and rescue services and increase the efficiency of their work.

Basic material and results. One of the key areas of improving the efficiency of maritime transport management and ensuring shipping safety is reducing the time for organizing and conducting search and rescue operations. This involves optimizing the duration of the management cycle - from collecting and processing information to making decisions and transmitting coordination commands to performers.

According to the logistical approach, such optimization is considered as a process of increasing the efficiency of managing information flows, resources and actions within a single maritime transport system.

The application of methods of the queuing theory allows formalizing the patterns of receipt, sequence and processing of requests in the dynamic environment of maritime transport [1, 30].

Let's consider the process of processing requets for search and rescue operations within the maritime transport logistics system using the provisions of the queuing theory (Fig. 1).

The system for organizing search and rescue operations at sea can be considered as an element of managing logistical flows in the maritime transport system, which combines information, material and human resources in order to ensure the continuity of the process of responding to emergency events. Such a system operates on the principles of adaptive management, where management decisions are made taking into account the real state of the load and the priority of tasks.

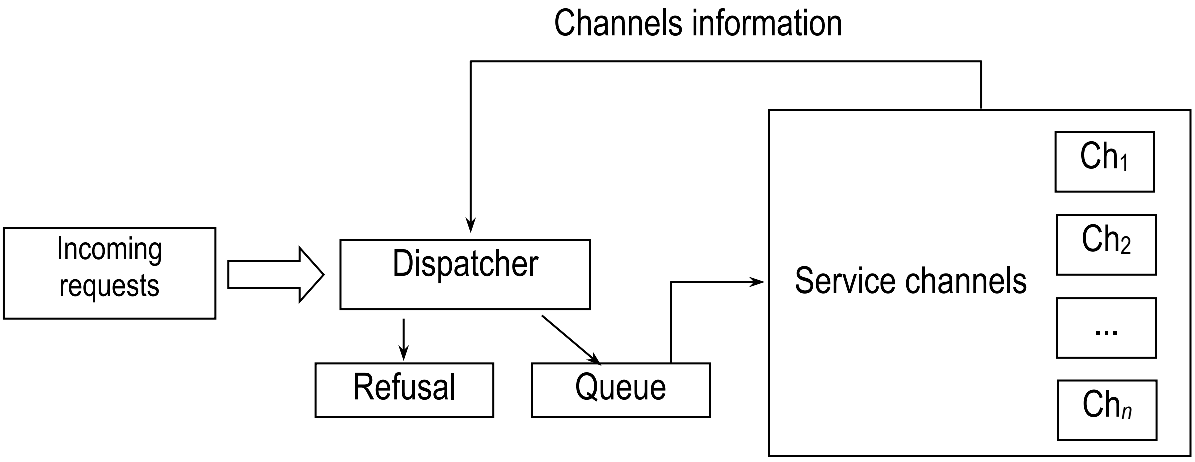

Figure 1 – Processing rescue requests using the principles of the queuing theory
Source: developed by authors

Its structure includes a number of interconnected stages typical for logistics processes in maritime transportation:

information and analytical unit collects and initially processes requests from vessels that find themselves in difficult navigation conditions;

coordination and dispatch center (human or automated system) ensures registration of requests, determines the procedure for their execution, routes information flows to executive units (State Maritime Rescue Coordination Center, Maritime Rescue Subcenter) and can form a queue in case of system overload;

queue-storage unit functions as a regulator of logistical flows, ensuring optimization of priorities and resource use;

service node forms the structure of response channels according to the type and scale of the event;

service channels reflect the operating states of the system ("free", "busy", "inoperative") and determine the real throughput capacity of the rescue network;

service refusal is the result of exceeding the system's capacity or individual channels failing, requiring management intervention to reallocate resources.

In the event of emergencies at sea, one of the key efficiency indicators of the maritime search and rescue system is the timeliness and quality of response to information flows about disaster events. An appropriate response requires not only the technical readiness of units, but also a high level of coordination, information interaction and management consistency between all links of the logistics system.

Effective management includes: prompt reception of messages, rapid search coordination, rational allocation of resources and ensuring continuity of the management cycle - from the receipt of a signal to the completion of the rescue operation. Fulfilling these conditions allows to significantly reduce time, increase the stability of functioning and efficiency of the maritime rescue system.

Requests for rescue operations are received by the system at random moments of time, which determines the stochastic nature of the management process. Similarly, the duration of processing each request depends on the complexity of the situation, geographical conditions, type of vessel and other factors, therefore it has a random nature. In terms of the queuing theory, the receipt of each request to the system is considered as *the event*, and the set of such events forms *the input flow*. In turn, the execution of requests and the completion of operations constitute *the output flow*, which reflects the throughput of the system and the level of its organizational coherence.

The mathematical apparatus of the queuing theory allows us to quantitatively assess the efficiency of the logistical management of the search and rescue process depending on the characteristics of the request flows, the selected discipline of their service and the level of resource utilization [1; 2].

The indicators obtained in the modeling process make it possible to assess the behavior of the system not only in the conditions of a single event, but also in the medium-run period, which is especially important for resource planning and load forecasting in the field of maritime transportation.

In the research, the incoming flow of information messages (requests) about emergency situations at sea is considered as the simplest flow of events. This approach is appropriate, since it is the simplest flows that most often describe the nature of the arrival of distress signals in real conditions of maritime transport operation.

In a search and rescue management system, this means that the moment of receipt of each request is random and does not depend on previous events, which allows the use of the Poisson model to estimate the intensity of the flow.

The simplest flow of requests has the following properties:

– randomness and independence of events: the receipt of the next request does not depend on the time of receipt of the previous one;

– stationarity of the flow: the intensity of the receipt of request (λ) remains constant during the analyzed period;

– constant average intensity: the average number of requests received per unit of time does not change within the selected observation interval;

– ordinariness: at any given time, only one request is received in the system; the probability of simultaneous receipt of two or more requests is insignificant;

– mass nature of the process: during large-scale events (storm, accident, mass accumulation of vessels), the number of requests can increase significantly, but the general pattern of the flow remains close to the Poisson model.

The request of the simplest flow model in the logistic analysis of maritime search and rescue systems allows to quantitatively describe the load on the control system, to estimate the probability of overloading of service channels, and to optimize the distribution of resources in space and time. This approach provides the basis for building adaptive algorithms for responding to and predicting situations in the field of maritime transport safety.

As noted in [2], in most practical cases, the efficiency of the functioning of maritime search and rescue systems can be adequately assessed by replacing complex non-stationary request flows with simpler ones, provided that they have the same intensity density. This is explained by the fact that the sum of a large number of ordinary and stationary flows with different aftereffect parameters forms the resulting flow, which in its characteristics approaches the simplest. Such an effect is analogous to the action of the central limit theorem, according to which the total influence of individual random processes tends to normalize.

However, in real conditions of operation of marine control systems, the flow of requests rarely remains stationary. The non-stationarity of information flows is most clearly manifested during the occurrence of mass or sudden events – when the intensity of incoming signals increases sharply. This is typical for periods of increased navigation activity, in particular in the summer, when the number of small tonnage vessels, yachts and passenger routes increases. Under such conditions, the probability of accidents increases, in particular, loss of control of vessels during storms, damage to the hull, or the need to provide emergency medical care to the crew, which forms peak loads on the maritime search and rescue system [2].

To ensure the stable operation of the system in such conditions, indicators of the success of the actions of the Search and Rescue Service at Sea are used, which allow assessing its efficiency from two interrelated positions – operational reliability and logistical productivity. The main indicators include:

– maximum system throughput (the number of requests that can be processed per unit of time during extreme situations);

– average waiting time for request service (minimization of downtime in the queue);

– service channel load factor (degree of use of system resources);

– economic efficiency of the service operation – maximizing the result from the use of available resources in a given time interval.

Comparative analysis of different configurations of the Maritime Search and Rescue Service allows to determine the optimal parameters of its functioning, to find a rational balance between the speed of response, reliability and resource costs, as well as to formulate recommendations for improving the structure of the service. Thus, the integration of mathematical models of mass service into management solutions allows to increase the efficiency of maritime logistics security systems and reduce time losses during rescue operations.

To practically confirm the efficiency of the request of the queuing theory provisions, we will consider a number of elementary operations of managing the flow of requests aimed at reducing the time for processing information, making decisions and delivering commands to the executors. The implementation of these processes is significantly influenced by random factors, such as weather conditions, the number of simultaneous emergency events or the technical condition of rescue vehicles.

Let the Maritime Search and Rescue Service receive approximately two requests at random every 10 hours. Determine the probability *$p_i(t)$* flow of receiving an average of four requests in 30 hours.

The probability flow of applications received in a time period *t* is calculated using the formula:

$$p_i(t) = \frac{(\lambda \cdot t)^i}{i!} e^{-\lambda \cdot t}, \quad i = 0, 1, 2, \dots \tag{1}$$

The following notations are introduced in formula (1):

λ – intensity of requests: $\lambda = \frac{2}{10} hour = 0.2\ (hour)^{-1}$;

t – time during which request were received: $t = 30\ hour$;

i – number of requests (messages): $i = 4$.

Then:

$$p_4(t) = \frac{(0.2 \cdot 30)^4}{4!} e^{-0.2 \cdot 30} = \frac{6^4}{24} e^{-6} = \frac{1296}{24} 0.025 \approx 0.134.$$

i.e. the probability flow of four requests for service within 30 hours is $p_4(t) \approx 0.134$.

In the second example, let's consider a situation where the Maritime Search and Rescue Service receives an average of about 1.2 requests per hour during extreme conditions, during mass search and rescue operations. The average duration of one call is 10 service minutes.

It is necessary to determine the main characteristics of the queue system and evaluate the efficiency of its operation.

Input data:

– incoming flow of requests – the simplest with intensity $\lambda = 1.2\ (hour)^{-1}$,

– the intensity of the flow of service requests has

$$\mu = 10 (min)^{-1} = 0.17\ (hour)^{-1},$$

– service channel load factor: $\rho = \frac{\lambda}{\mu} = \frac{1.2}{0.17} = 7.06$.

Probability of service of the request $p_{serv} = p_0 = \frac{1}{1+\rho} = \frac{1}{1+7.06} = 0.12$.

Probability of service refusal $p_{ref} = p_1 = \frac{\rho}{1+\rho} = \frac{7.06}{1+7.06} = 0.88$.

Thus, the system serves only 12% of calls, which is unsatisfactory.

Absolute system throughput $A = \lambda \cdot p_{serv} = 1.2 \cdot 0.12 = 0.144\ (hour)^{-1}$, that is, on average, requests are served per hour.

The results obtained indicate that the traditional model of information flow management in the search and rescue service does not meet modern requirements for speed of response and adaptability. To increase the efficiency of the system, it is advisable to implement intelligent logistics technologies (IQ technologies), which provide:

– automated processing of incoming signals in real time;

– analytical forecasting of the load on service channels;

– optimization of the order and priority of requests;

– integration of information flows with marine vessel monitoring systems (AIS, SAR, VTS).

Thus, the use of mathematical modeling in combination with intelligent logistics technologies allows you to create an adaptive management system for maritime search and rescue operations, which ensures reduced response time, increased reliability of solutions, and efficient use of resources within the transport and logistics infrastructure of the maritime sector.

Conclusions. As a result of the research, it was substantiated that the application of the queuing theory is an effective scientific and methodological basis for optimizing the management of search and rescue operations at sea. The developed mathematical model allows us to quantitatively assess the efficiency of the system, taking into account the random nature of the receipt of requests, the limited throughput of service channels and the stochastic features of maritime emergencies.

It is shown that the simplest flow model, which is based on the Poisson distribution, adequately describes the statistical nature of the receipt of rescue requests in maritime logistics systems. This approach allows us to assess the level of system loading, the probability of service requests, the average waiting time and the risk of channel overload, which are key indicators of the operational efficiency of rescue coordination centers.

The results of analytical calculations show that in conditions of high intensity of incoming signals, the current search and rescue system is able to service only about 12% of incoming calls, which indicates a low level of throughput and the need to modernize the information and management infrastructure. This necessitates the introduction of intelligent decision-making support technologies (IQ technologies).

Such technologies provide automated data processing in real time, analytical forecasting of the load on service channels, dynamic prioritization of requests and integration with vessel traffic monitoring systems (AIS, SAR, VTS). Their implementation increases the adaptability of management processes and improves coordination between units within maritime logistics systems.

The scientific novelty of the research lies in integrateing the principles of logistics, cybernetics and management sciences, forming a comprehensive model of adaptive decision-making in the maritime transport safety system. The research contributes to the development of interdisciplinary methods that combine mathematical modeling, information flow management and risk analysis within a single management paradigm.

The practical significance of the results obtained lies in the possibility of their use to increase the efficiency of maritime coordination and rescue centers, the creation of digital emergency management systems, as well as the modernization of training programs for maritime specialists in the fields of logistics and security management. The proposed model can serve as the basis for the development of intelligent search and rescue operations management systems that can optimize resource allocation and minimize response time in conditions of uncertainty.

Prospects for further research include empirical verification of the proposed model in real-world conditions of maritime rescue services, as well as the development of hybrid algorithms that combine mathematical modeling, artificial intelligence, and predictive analytics. Such research will contribute to the creation of modern decision support systems that integrate technological, organizational, and human factors, increasing the resilience and efficiency of the maritime transport sector as a whole.

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