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ANALYSIS OF THE RELIABILITYOF THE NAVIGATION COMPLEX AND RECOMMENDATIONS FOR INCREASE OF RELIABILITY

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The article examines the navigation complex as a mass service system and examines the relationship between the complexity of sea conditions and the capabilities of the system. Mathematical modeling and reliability analysis of the ship's navigation complex from the perspective of mass service theory were carried out. The presented work is one of the first in the application of mass service theory in the analysis of safe shipping problems, which ensures its importance and scientific novelty. The developed mathematical model was implemented in numerical experiments, and the obtained results were mathematically processed and visualized by building approximation equations of the second order, which relate the probability of the operating state of the system to the corresponding intensities of failure and maintenance flows. Mathematical modeling was carried out for different conditions of navigation complexity (from coastal to inshore navigation and port maneuvers). This ensures the high practical importance of the model results in the development of relevant maritime regulations and the assessment of the benefits of electronic navigation. A four-factor linear regression was built, which connects the reliability of the navigation complex with the corresponding flows of failures and maintenance in the system. The obtained regression is visualized in a nomogram, which is suitable for solving a number of practical problems.
Keywords: *navigation systems; system stability;reliability; technical factor; queuing systems; system failure and recovery; flow of requests; quadratic approximation; nomogram.*

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Introduction. In the period from 2011 to 2018, there were 23073 maritime accidents and incidents in the fleets of European Union member states or in EU maritime administrative waters, as stated in reports by the European maritime safety agency. In relation to this extensive amount of incidents, 699 individuals perished, 7694 individuals sustained injuries, 230 vessels were completely destroyed, and over 566 instances of ocean contamination occurred. Hence, maritime accidents and incidents have caused greater economic and environmental consequences in recent times. It was claimed that maritime disasters could have a lasting impact on the ecosystem and environment of a region. This is why authorizations and international alliances are beginning to thoroughly analyze the underlying reasons of marine accidents and incidents, and then assess them in order to manage the outcomes and seek ways to minimize them. This research project combines a narrative review of pertinent articles with library studies of annual reports from the European Marine Casualty Information Platform to analyze data and effective factors of maritime accidents. It then suggests policies and strategies to decrease accidents and incidents related to those factors [1].

The safety of marine transportation relies entirely on the secure state of a ship's deck and machinery. Having a strong technical knowledge and expertise is required for seafarers, analysts, and researchers to achieve this. Based on the Marine Accident Investigation Branch (MAIB) reports from 1993 to 2012, 6,692 maritime incidents can be traced back to technical causes alone, with 69% of incidents being a result of various factors combined. The technical aspects include main/auxiliary/deck machinery, bridge operations, maneuverability, collision/contact, electrical systems, fire and explosion prevention, flooding and sinking risks, management protocols, ship activities, grounding dangers, hazardous events, navigation and communication devices, design considerations, pollution issues, stability measures, structural strength, safety apparatus, and emergency response procedures, among other things. Throughout the history of mankind, a commonly used strategy has been to learn important lessons from previous negative experiences, which in turn enables people to prevent similar occurrences in the future [2].

Through better maintenance, design standards, training, and monitoring, the maritime sector can lessen accidents' impact and strengthen safety levels at sea. Enhanced maintenance protocols, improved design standards, crew training on new technologies, and continuous monitoring of systems are essential to avoid accidents caused by technical problems [3, 4].

Analysis of recent research and publications. Numerous methods have been found for analyzing the reliability of electronic navigation systems, with a main emphasis on assessing the reliability features of both the system as a whole and its individual subsystems [5]. Certain studies about the reliability of navigation systems mention the definition of reliability as the susceptibility of a navigation device or specific system or component (if present) to errors during a specified timeframe and specific conditions. It indicates the likelihood of carrying out a specific task without any incidents happening. The mean time between failures (MTBF) is a distinctive parameter that is utilized to define reliability. This is the typical length of time between consecutive system or system component failures. Along with reliability, IALA [6] also outlines availability, which is described as the likelihood of an aid or aid system carrying out its designated function under specific conditions at a randomly chosen moment. The mean time to repair (MTTR) parameter is utilized for availability assessment.

In terms of examining the reliability of DGPS systems, Specht [7, 8] discussed the reliability framework of the system and its components with regards to their functions and interconnections. Components and systems were subsequently given two states based on their operation: 0 for failure, 1 for normal function. Additionally, the navigation system's dependability is evaluated over a set period, known as the system's survival probability, taking into account the specified reliability framework. The reliability of the navigation system and its marginal reliability within a specific time frame were calculated based on an exponential lifetime and downtime distribution assumption.

The analysis of AIS system availability, as developed by Jaskólski [9–11], is utilized for Markov chains. Three different states of the system (functioning, interim, and breakdown) were identified based on the availability factor of AIS data transmission being monitored. Afterward, the likelihood matrix of transition probabilities among distinct states of AIS availability was established. The matrix was formed using the intensity of state transitions identified by analyzing AIS base station signals that were recorded. Ultimately, the probability of the system staying in each operating state was established by considering the initial and aggregate distributions of transitions between specific states.

The evaluation of electronic transmission system reliability regarding electromagnetic interference, as outlined by Paś and Rosiński [12, 13], includes three levels: full functionality, security priority, and inadequate security. This was accomplished by differentiating among states. The Chapman-Kolmogorov system of equations was used to describe the analyzed system by defining transitions between certain safe states. The initial conditions were then implemented and the Laplace transform was utilized to calculate the likelihood of the system staying in a specific state. Moreover, the likelihood of the system staying operational was determined by tracking the switch rate between particular states and the likelihood of staying in one state. Applications that assess the dependability of electron transport systems rely on the belief that the transition times between particular safety states follow an exponential distribution.

Sumic et al. [14–16] utilized the Markov model to examine the dependability and accessibility of an ECDIS system with a main (master) and secondary subsystem (backup subsystem). The primary and standby systems create a parallel setup in which, if each subsystem can be in working or non-functioning condition, the system can be in one of four states. By utilizing Markov model characteristics (where the likelihood of future states is based solely on the current state; the subsequent state is determined only by the current state, not by the events leading up to it), the system's reliability was calculated as the probability of not being in a state of failure. The primary finding of the research was that the intended level of reliability was not reached. This led the authors to suggest a different approach, known as the cold standby system, which involves incorporating backup systems connected in series or parallel.

Purpose and objectives of the research. Using queuing systems theory is a widely used way to assess technical systems' effectiveness. This theory enables us to compute the likelihood of various states within a queuing system (QS) and to establish the connection between specific QS parameters and metrics of its efficiency.

If all channels in the system are considered basic channels, the operation QS is currently undergoing can be characterized as a Markov random process. This procedure involves distinct stages and takes place continuously over a period of time. If the ergodicity condition is met, the system reaches the final steady-state state. In this state, probabilities of states and other process parameters do not depend on time. Researchers frequently concentrate on these well-established, enduring traits.

Main body. Inconsistent utilization of QS is caused by irregular application flows and varying processing times. At times, incomplete orders may accumulate at the entrance, causing an overload in quality assurance. On the other hand, in some cases the QS input may have a channel ready but no tasks, causing the QS to be underused and leaving the channel unused. There is an accumulation of orders at the entrance of QS. These orders can result in one of two possible outcomes. Those who cannot wait any longer in the queue will either be added to the queue or leave the QS without service [17].

In case of a channel failure, the recovery process starts right away. This could involve waking up, receiving the necessary treatment for healing, or recovering effectively from the incident.

The birth and death graph represents the state of the system and is shown as:

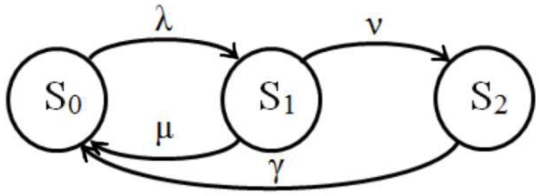

Figure 1 – QS state graph

where S_0 – channel is free;

S_1 – channel is busy (working), good;

S_2 – channel failed, restored.

Let the simplest request flow arrive at its input with an intensity denoted by λ. Service time – exponential with parameter $\mu = \frac{1}{\bar{t}_{обсл}}$, where $\bar{t}_{обсл}$ – average request service time. This means that the service flow is the simplest, i.e., a stationary Poisson process can be described by an intensity parameter denoted by μ. A functioning channel may fail and be rejected. Let us assume that the simplest form of intensity ν is proportional to the error flow. Immediately after a channel failure, the channel restoration process begins. The channel repair time follows an exponential distribution characterized by a parameter called intensity $\gamma = \frac{1}{t_p}$, where t_p – average recovery time (repair). In [18], the problem was expressed in a similar way, focusing on the navigator as a service channel. In this study, the complexity of the problem arises from considering the possibility of the occurrence of channel disturbances and their influence on the resting state, denoted by an intensity ν′. It is reasonable to assume that ν′ <ν [19].

The graph representing the QS status will exhibit the following appearance:

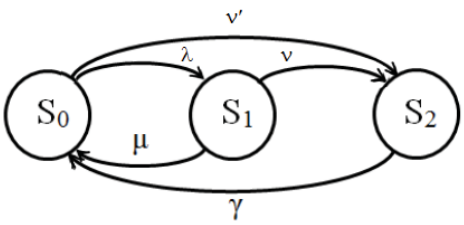

Figure 2 – QS state graph with failure possibility during idle

We will now calculate the ultimate likelihood of the system state and its validation characteristics. A stands for total throughput, while Q stands for throughput as a probability of processing incoming requests successfully.

The state probability in a system of algebraic equations is determined by the Kolmogorov differential equation when the left-hand side is set to zero, resulting in the final probability expression:

$$\begin{aligned}(\lambda+\nu')p_0 &= \mu p_1 + \gamma p_2\\ (\mu+\nu)p_1 &= \lambda p_0\\ \gamma p_2 &= \nu p_1 + \nu' p_0\end{aligned} \tag{1}$$

Additionally, conditions for normalization to unity can be integrated into this system:

$$p_0 + p_1 + p_2 = 1 \tag{2}$$

The task is to determine the intended final probability:

$$p_0 = \left[1 + \frac{\lambda}{\mu+\nu} + \frac{\lambda\nu + \mu\nu' + \nu\nu'}{\gamma(\mu+\nu)}\right]^{-1} \tag{3}$$

$$p_1 = \frac{\lambda}{\mu+\nu} p_0 \tag{4}$$

$$p_2 = \frac{\lambda\nu + \mu\nu' + \nu\nu'}{\gamma(\mu+\nu)} p_0 \tag{5}$$

To determine the relative throughput, we apply the principles described in [10] and obtain the following result:

$$Q = p_0 \frac{\mu}{\mu+\nu} \tag{6}$$

Absolute throughput:

$$A = \lambda Q = p_0 \frac{\lambda\mu}{\mu+\nu} \tag{7}$$

By simplifying the expression for Q, we can write it into a form suitable for numerical calculations:

$$Q = \frac{\mu\gamma}{(\mu+\nu)(\gamma+\nu') + \lambda(\gamma+\nu)} \tag{8}$$

Results of research. The probability of processing an incoming request Q is determined by five parameters. These parameters are the corresponding flow intensities: λ, μ, γ, ν и ν'.

The value of Q will be calculated for various combinations of the specified parameters. The calculations of the fulfillment probabilities of incoming requests in different sail conditions and the intensities of incoming request flows, failed flows and return flows are presented in Figures 3–6.

Correlations for sailing in coastal areas are shown in Figures 3–4. In this scenario, the failure flow intensity increases to 1, while the request flow intensity varies from 10 to 20. As a result, the chances of fulfilling requests decrease compared to the previously mentioned information.

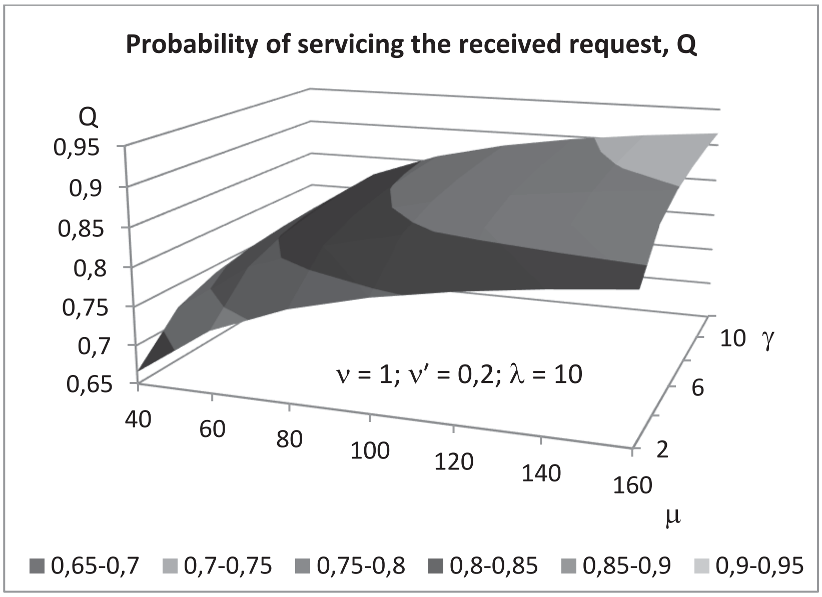

Figure 3 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding flows are as follows: ν = 1 per hour; ν′ = 0,2 per hour; λ= 10; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_т = 0{,}5098 \pm 0{,}01 + (0{,}0258 \pm 0{,}0018)\gamma + (-0{,}0013 \pm 0{,}0001)\gamma^2 + (0{,}0036 \pm 0{,}0002)\mu + (-1{,}2002 \times 10^{-5} \pm 0{,}0912 \times 10^{-5})\mu^2 \quad (9)$$

$R^2 = 0{,}9839$; $\sigma = 0{,}0082$.

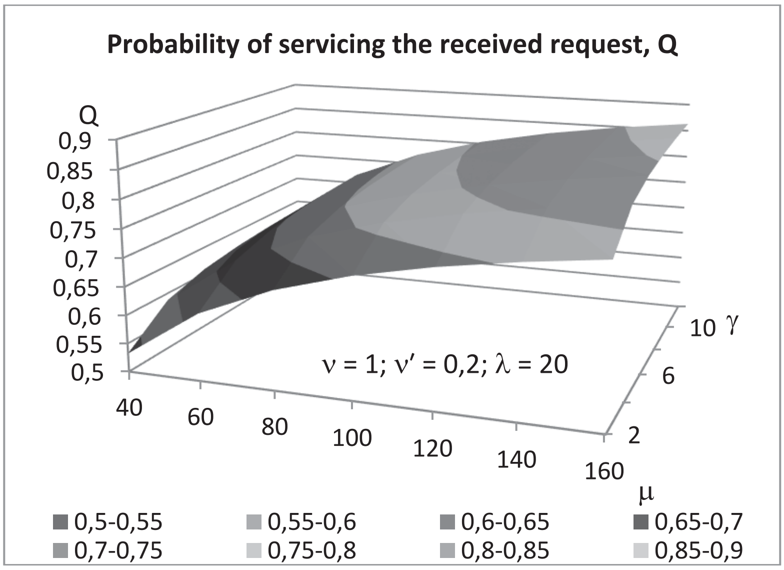

Figure 4 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding flows are as follows: ν = 1 per hour; ν′ = 0,2 per hour; λ= 20; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_т = 0{,}3222 \pm 0{,}011 + (0{,}0275 \pm 0{,}002)\gamma + (-0{,}0014 \pm 0{,}0001)\gamma^2 + (0{,}0051 \pm 0{,}0002)\mu + (-1{,}6011 \times 10^{-5} \pm 0{,}101 \times 10^{-5})\mu^2 \quad (10)$$

$R^2 = 0{,}9897$; $\sigma = 0{,}0091$.

In difficult navigational conditions such as rivers, harbors, heavy traffic and poor visibility, Figure 5–6 illustrates the relationships observed in sailing. The failure flow intensity increases to 5, while the request flow varies from 20 to 40, further reducing the probability of a request being completed compared to previous data.

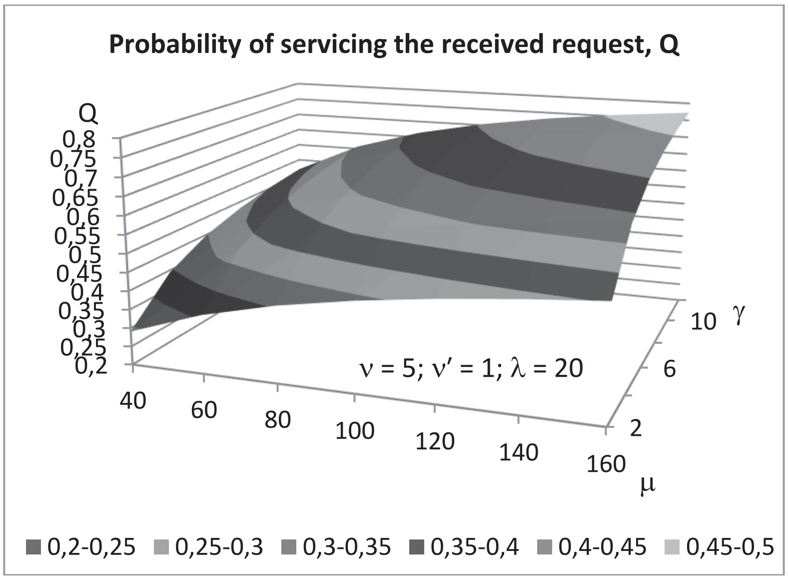

Figure 5 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding flows are as follows: ν = 5 per hour; ν′ = 1 per hour; λ= 20; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_т = -0{,}0095 \pm 0{,}0163 + (0{,}0667 \pm 0{,}003)\gamma + (-0{,}0031 \pm 0{,}0002)\gamma^2 + (0{,}0049 \pm 0{,}0003)\mu + (-1{,}5023 \times 10^{-5} \pm 0{,}1487 \times 10^{-5})\mu^2 \quad (11)$$

$R^2 = 0{,}989$; $\sigma = 0{,}0134$.

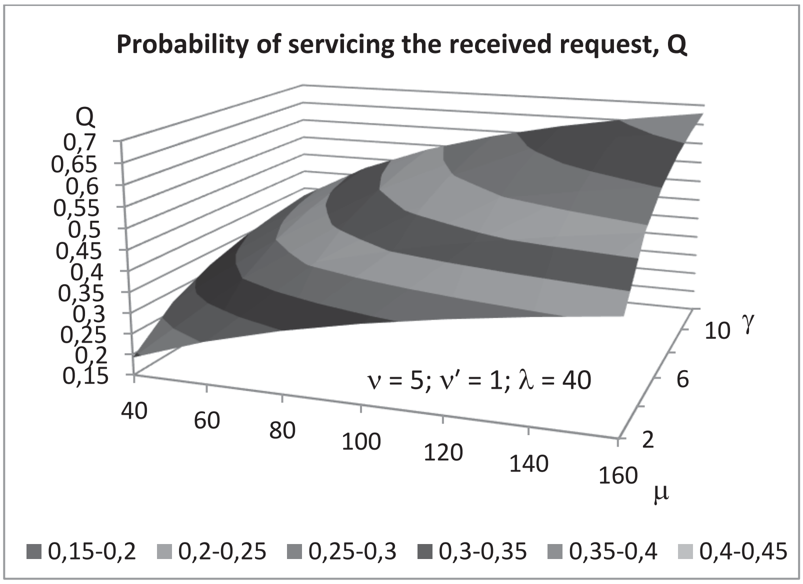

Figure 6 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding flows are as follows: ν = 5 per hour; ν′ = 1 per hour; λ= 40; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_т = -0{,}1196 \pm 0{,}0171 + (0{,}0604 \pm 0{,}0031)\gamma + (-0{,}0027 \pm 0{,}0002)\gamma^2 + (0{,}005 \pm 0{,}0003)\mu + (-1{,}3831 \times 10^{-5} \pm 0{,}1561 \times 10^{-5})\mu^2 \quad (12)$$

$R^2 = 0{,}9886$; $\sigma = 0{,}014$.

The equations below each graph are derived using a square two-factor approximation method. The high level of the coefficient of determination (R^2=0,98-0,99) indicates that the obtained square statistical model is very appropriate. The standard deviation of the quadratic regression is significantly lower (σ=0,006-0,014), indicating its excellent accuracy. Therefore, these models can be safely used to obtain reliable probability estimates [20, 21].

Analysis of equations (9) and (10), which were obtained with the same values ν=1.0 and ν'=0.2, but with different intensity of the flow of requests λ, shows that an increase in λ from 10 to 20 reduces the probability of servicing an incoming request Q (relative throughput ability) by 0.2.

In this case, the coefficients for μ and μ^2 increase by approximately one and a half times, while the coefficients for γ and γ^2 remain practically unchanged. This means that keeping Q high depends largely on μ rather than γ.

At the same time, analysis of equations (11) and (12) shows that an increase in the intensity of the failure flow of channel ν from 1 to 5 (ν' from 0.2 to 1) with the same intensity of the flow of requests (λ=20) reduces Q by 0.3. In this case, the coefficient for γ increases by 2.4 times (for γ^2 by 2.2 times), although the coefficients for μ and μ^2 practically do not change.

This means that keeping Q high depends largely on the channel restoration intensity γ rather than on the service flow intensity μ.

Thus, the system responds to an increase in the intensity of the flow of requests λ by increasing the role of the intensity of the service flow μ and, conversely, with an increase in the intensity of the flow of failures ν, the system responds by increasing the role of the intensity of the recovery flow γ.

In our opinion, the system in this case acts very physically and logically. The data are also consistent with the following recommendations for the operation of bridges in various difficult navigation conditions [22].

Table 1 – Watch conditions on the bridge as they relate to sailing conditions

	Open Water	***Restricted Water, Anchoring, Embarking or Disembarking a Pilot***	***Entering or Leaving Port***
Clear weather, little or no traffic	I	II	III
Clear weather, heavy traffic	II	II or III	III
Restricted visibility, little or no traffic	II	II	III
Restricted visibility, heavy traffic	II or III	II or III	III
Pilotage	I	I or II	II or III

Bridge Watch Condition – I

To fulfill this condition, the bridge must have both an Officer of Watch and a Lookout present on the bridge.

The Watch Officer performs regular watch duties and sometimes acts as the only watch during the day. In conditions requiring manual control, it is important to note that the skipper cannot act as an observer. Therefore, it is necessary to appoint an additional team member as a dedicated monitor. The engine room has the ability to operate in both manned and unmanned modes.

Bridge Watch Condition – II

To fulfill this requirement, the following persons must be on the bridge: the Master or Chief Officer, the Officer of Watch, the Lookout, and the Helmsman.

The safe navigation of the crew and general watch arrangements are supervised by the Master or Chief Officer. A Watch Officer assisting the Master or Chief Officer provides relevant information, steers the ship and supervises the execution of orders. In situations deemed necessary by the crew or in difficult conditions, such as heavy traffic, limited visibility, port maneuvers or pilot embarkation, the helmsman takes over control of the ship manually.

It is important that the engine room is always staffed, but ultimately it is up to the Master to assign personnel there or not.

Bridge Watch Condition – III

To fulfill this condition, the following persons must be on the bridge: the Master, Officer of Watch, Additional Officer, Lookout, and Helmsman.

In condition III, the Watch Officer is relieved of collision monitoring duty and an additional officer assumes that role using AIS/ARPA systems. They provide the Watch Officer with significant navigational information and information about nearby vessels. It is imperative that personnel are present and ready in the engine room.

Also, the statistic modeling of the numerical experiments was performed. To that end, a 4-factor linear regression for the dependence of Q's magnitude on all 4 factors (λ, ν, γ, and μ) was built. The multiple regression equation received is included in Fig.7.

Regression analysis was carried out on the basis of 168 dots on 4 variables.

$$Q_т = 0{,}6377 \pm 0{,}0138 + (0{,}0157 \pm 0{,}001)\gamma + (0{,}0018 \pm 8{,}678 \times 10^{-5})\mu + (-0{,}0412 \pm 0{,}0024)\nu + (-0{,}0063 \pm 0{,}0004)\lambda \quad (13)$$

$$R^2 = 0{,}9329;\ \sigma = 0{,}045.$$

The received equation is visualized via nomogram, which allows to rapidly perform any necessary calculations and estimations.

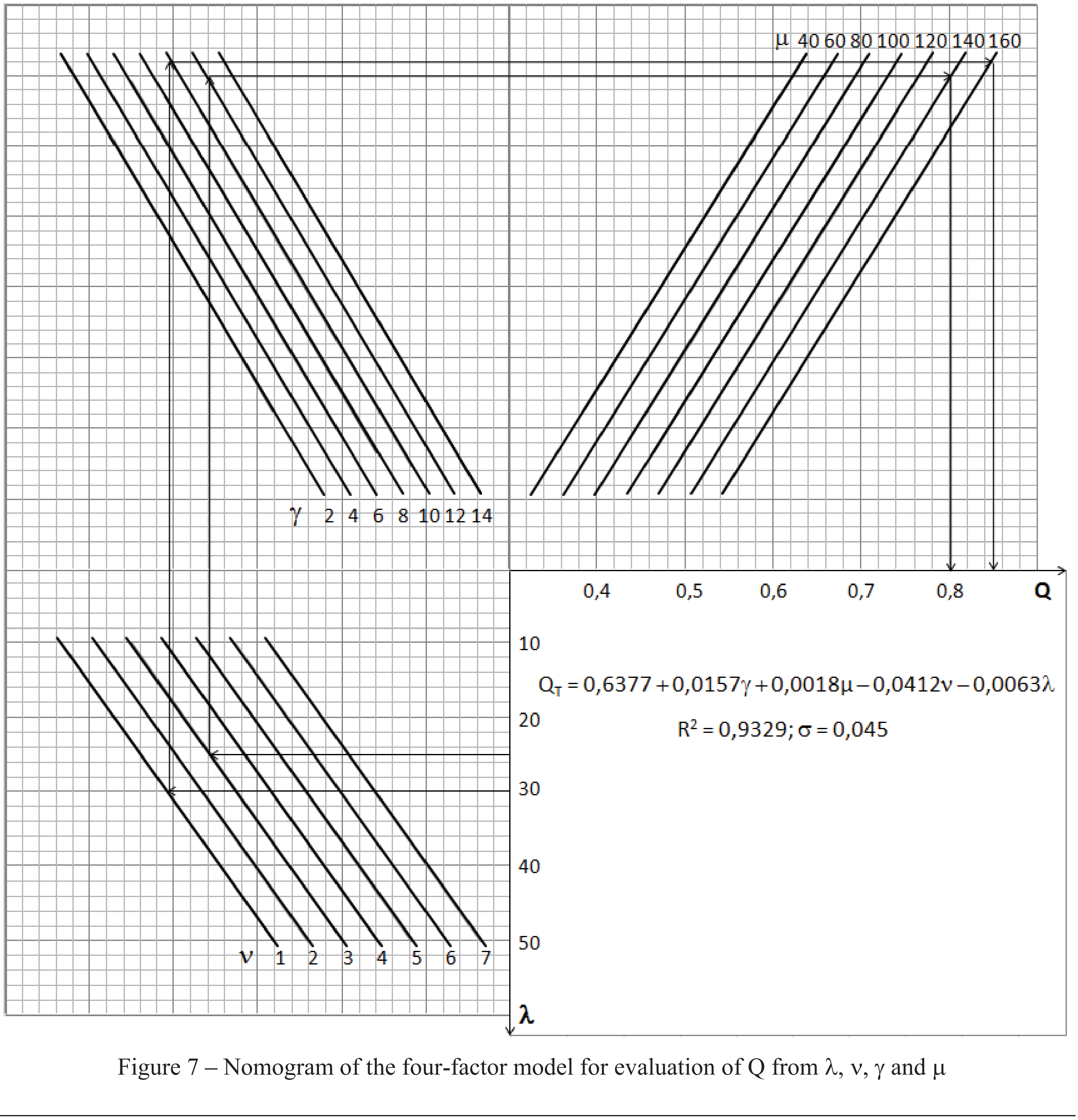

Figure 7 – Nomogram of the four-factor model for evaluation of Q from λ, ν, γ and μ

The given model has a high indicator of the coefficient of determination R^2=0.9329, which shows the high adequacy of the built model and the standard error of the regression is acceptable for practical use.

We will give several examples of the use of the nomogram.

Example 1. We choose the value of theλ (for example, 30), we move in the direction of the arrow to the left, choosing the value of ν (in this case, it is 1), we move up on the arrow to select the value of γ (in the given example it 10), moving along the arrow to the right in the first quadrant we choose the value of μ (in our example it is 160) and at the very end we go down arrows down on the Q axis, we will get its' value.

Example 2. The reverse direction of movement along the nomogram is also possible, i.e. solving the inverse problem: given the desired values and moving along the nomogram against the time arrow step by step, we choose the values of the input parameters of the model that would ensure the given value of Q. This task has many possible solutions and depends on the real possibility of ensuring one or another level of each of the factors, in the end, on the degree of their real reach.

Example 3. The use of the nomogram is not limited to the given example. Oncoming traffic is also possible: according to the given diagram. For example, by setting the desired Q value and the known values of some factors from model, it is possible to find the necessary values of other factors that would ensure the achievement of the selected Q. With such a formulation of the problem, the nomogram makes it possible to determine the existence of a solution and, if it exists, to determine the set of possible values for the factors that are determined, as well as the rate of their substitution (within certain limits, a decrease in the value of one of the factors can be compensated by an increase in the value of another factor).

Example 4. The given nomogram provides wide opportunities for estimating the possible limits of Q values, if the limits in which the input factors of the model can change are known. That is, if the limits in which the values of each of the factors can be found with some confidence are known, it is possible to move along the given nomogram gradually from one factor to another with a "strip" of values, where each "strip" reflects the limits of variation of the possible values of this factor. At the end of this process, we will reach the corresponding "band" of Q values, that is, we will have estimates of possible deviations from the average forecast Q value (pessimistic and optimistic forecast).

Conclusions. Through the examination of the simulation findings, it is possible to identify how the initial parameters impact the likelihood of meeting a request that is incoming. This enables forecasting the stability of navigation system components. The results obtained offer a chance to create suitable suggestions for enhancing the functional stability of navigation systems. The results of the simulation indicate that there is a substantial decrease in the likelihood of fulfilling an incoming request as the failure rate and request rate increase. Therefore, the navigation complex's performance is reduced.

Therefore, creating stability models for navigation systems allows for the simulation of different emergency scenarios, enabling quick calculation and estimation of various possibilities through the nomogram visualization obtained through linear regression. The simulation exposed the connection between the performance of the system and its parameters: λ, μ, γ, ν, ν'. On the other hand, systems have numerous internal links. Not following these rules could lead to the system not working properly.

This research emphasizes the need to establish the correct level of redundancy for navigation devices in order to guarantee system reliability. Should the Q value drop under 0.7, a critical scenario will take place aboard the vessel. Figures 3–6 demonstrate how the acceptance of a request is influenced by the navigational conditions of the journey. Hence, steps need to be implemented to guarantee the stability of the navigation system even under challenging circumstances.

Research findings can enhance comprehension of the dangers present as well as their associated levels of risk. Even with the increasing attention in the area, as shown by the rise in publications, it is crucial to recognize the scarcity of literature and highlight the necessity for more research. Conducting a thorough hazard analysis is advised, with a focus on categorizing the hazards in greater detail. This method enables a thorough assessment of impact factors, resulting in improved risk management plans that are more precise and efficient.

REFERENCES

1. Behbood Issa Zadeh. (2022). Analysis of European Union Maritime Casualties Crisis Management Prospective. *The 12th International Conference on Recent Development in Managements and Industrial Engineering: Dusseldorf, Germany*.doi: 10.5281/zenodo.8134918.

2. Yip, Tsz L., Sahin, B. (2020). Technical factor in maritime accidents: an index forsystematic failure analysis. *IAME 2020 Conference,* 1–11. doi: 10.17632/8p9hsvfhmx.2.

3. Maternová, A., Materna, M., Dávid, A., Török, A., Švábová, L. (2023). Human Error Analysis and Fatality Prediction in Maritime Accidents. *Journal of Marine Science and Engineering*, *11*, 2287. doi: 10.3390/jmse11122287.

4. IMO. (2002). MEPC/Circ.392. Guidelines for formal safety assessment (FSA) for use in the IMO rule-making process. *International Maritime Organization: London.*

5. Blokus, A., Dziula, P. (2020). Reliability analysis of different configurations of master and back-up systems used in maritime navigation. *Journal of Marine Science and Engineering, 8,* 34; doi: 10.3390/jmse8010034.

6. IALA. (1989). Guide to the Availability and Reliability of Aids to Navigation. *International Association of Lighthouse and Aids to Navigation Authorities: Saint-Germain-en-Laye, France.*

7. Specht, C. (2003). Availability, Reliability and Continuity Model of Differential GPS Transmission. Annu. Navig. 5, 85.

8. Cydejko, J., Król A. (2002). Analiza wartości poprawek różnicowych z kilku stacji referencyjnych GPS, *Proceedings of XIIth International Scientific and Technical Conference – The Part of Navigation in Support of Human Activity on the Sea, Gdynia, Poland*.

9. Jaskólski, K. (2011). Application of Markov Chains to Analyse the AIS Availability. *Annu. Navig. 18,* 5–16.

10. Felski, A., Jaskólski, K. (2010). The problem of the inquiry unfitness of AIS system (in Polish), *Zeszyty Naukowe AMW, No. 4*.

11. Felski, A., Jaskólski, K. (2011). Analysis of the accessibility of the AIS system (in Polish), *Zeszyty Naukowe AMW, No. 3*.

12. Paś, J., Rosiński, A. (2017). Selected issues regarding the reliability-operational assessment of electronic transport systems with regard to electromagnetic interference. *Eksploat. Niezawodn. Maint. Reliab. 19,* 375–381.

13. Weintrit, A., Dziula, P., Siergiejczyk, M., Rosiński, A. (2015). Reliability and exploitation analysis of navigational system consisting of ECDIS and ECDIS back-up systems. *The monograph Activities in Navigation - Marine Navigation And Safety Of Sea Transportation*, editors: Weintrit A. London: CRC Press/Balkema, 109-115. doi: 10.1201/b18513-17.

14. Sumic, D., Perakovic, D., Jurcevic, M. (2014). Contribution to ECDIS reliability using Markov Model. *Trans. Marit. Sci. 3,* 149–157.

15. Ebeling, C. E. (2014). An Introduction to Reliability and Maintainability Engineering, Long Grove, Illinois: Waveland Press Inc.

16. O'Connor, P., Kleyner, A. (2012). Practical Reliability Engineering, fifth edition, West Sussex: John Wiley & Sons.

17. Aubakirov, S.K. & Selivyorstov, P.Y. (2016). System of mass service. Post capacity. *Bulletin of Science and Education*, *6*(18), 44–47.

18. Abramov, G.S., Makarchuk, D.V., Nosov, P.S. & Zinchenko, S.M. (2021). The ship officer as a failure-prone single-channel queueing system. *Materials of the 13th international*

scientific and practical conference "Modern information and innovation technologies in transport (MINTT-2021)", *13*, 157–162.

19. Abramov, G.S., Makarchuk, D.V. & Plotnikov, V.I. (2023). Analysis of the stability of marine navigation complex systems from the point of view of the QS. *Materials of the 15th international scientific and practical conference "Modern information and innovation technologies in transport (MINTT-2023)", 15*, 244–249.

20. Abramov, G.S., Plotnikov, V.I. & Zinoviev, V.I. (2023). Analysis of the reliability of the navigation complex and its influence on the functioning of the maritime logistics system. *Materials of the 1st International Scientific and Practical Conference "Transport, port, logistics, security: modern-day challenges and development prospects", 1,* 17–29.

21. Plotnikov, V.I., Dudchenko, S.V., Abramov, G.S., Makarchuk, D.V. (2023). Mathematical modeling and analysis of the reliability of the navigation complex. *Scientific Bulletin of the Kherson State Maritime Academy, № 26–27,* 82–95.

22. Columbia Shipmanagement. (2018). *Bridge Operations Manual BOPR-01.2*.

Абрамов Г. С., Плотніков В. І. АНАЛІЗ НАДІЙНОСТІ НАВІГАЦІЙНОГО КОМПЛЕКСУ ТА РЕКОМЕНДАЦІЇ ЩОДО ПІДВИЩЕННЯ СТІЙКОСТІ

У статті розглядається навігаційний комплекс як система масового обслуговування та досліджується зв'язок між складністю морських умов і можливостями системи. Проведено математичне моделювання та аналіз надійності суднового навігаційного комплексу з позицій теорії масового обслуговування. Представлена робота є однією з перших у застосуванні теорії масового обслуговування в аналізі проблем безпечного судноплавства, що забезпечує її важливість і наукову новизну. Розроблену математичну модель було реалізовано в чисельних експериментах, а отримані результати математично обробили та візуалізували, побудувавши апроксимаційні рівняння другого порядку, які пов'язують ймовірність робочого стану системи з відповідними інтенсивностями потоків відмов та обслуговування. Проведено математичне моделювання для різних умов навігаційної складності (від берегової до прибережної навігації та портових маневрів). Це забезпечує високу практичну важливість результатів моделі при розробці відповідних морських правил та оцінці переваг електронної навігації. Побудована чотирьохфакторна лінійна регресія, що пов`язує надійність навігаційного комплексу з відповідними потоками відмов і обслуговування в системі. Отримана регресія візуалізована в номограмі, яка придатна для вирішення низки практичних задач.

Ключові слова: *системи навігації; стабільність системи; надійність; технічний фактор; системи масового обслуговування; відмова та відновлення системи; потік запитів; квадратична апроксимація; номограма.*

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